Seawater Desalination Demonstration Program

Summary Report

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Report No. 1124

MWD
METROPOLITAN WATER DISTRICT OF SOUTHERN CALIFORNIA

ACKNOWLEDGMENTS

This report is a compilation of research efforts conducted coincident with one another by many individuals in several diverse organizations; a public water utility, a university research team, and an equipment and materials supplier. The preparation of this summary report included contributions from key individuals who either conducted or directed the research efforts, and then prepared reports to document the results of their unique research experiences. Thus, the development of this report reflects no one single author's work product, but rather the considerable efforts of several organizations and individuals. They are:

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CHAPTER 1
EXECUTIVE SUMMARY

BACKGROUND

The Metropolitan Water District of Southern California (Metropolitan) has pursued the development of the unlimited supply of seawater in the Pacific Ocean as a source of potable water for nearly 40 years. Metropolitan was first involved in a project to study the feasibility of desalinating seawater in 1959. This study investigated the applicability of various desalting processes in conjunction with appropriate energy sources for the distillation process. In the 1960s, Metropolitan acted as the lead agency in an effort by private and government agencies to begin the first large dual-purpose seawater desalination and electric power generating plant in the United States. The project, which would have involved construction of a nuclear power plant and a seawater desalination plant, was terminated in 1969 because of the escalating costs that plagued the American construction industry at that time. In the late 1980s, several new feasibility studies were conducted on dual-purpose electric power and desalination plants, including one underwritten by Metropolitan regarding desalting plants driven by steam supplied from a repowered fossil fuel power plant.

In a step-wise manner commencing in 1990, and continuing to the present, the Metropolitan Board of Directors has authorized staff to conduct a multiphased desalination program that would lead to the development and demonstration of an innovative process for distilling potable water from seawater. The goals of this program included the formulation of a process by which desalinated seawater could be produced at costs competitive with traditional water supplies, and the development of low-cost, durable construction materials for use in such desalination plants. The program established to accomplish these goals consisted of developing a conceptual process design and conducting an intermediate series of studies and investigations. The final activities of this program are to be the implementation of a 5 million-gallon-per-day (MGD) seawater desalination plant which will use these state-of-the-art materials and processes and will demonstrate the proposed technologies.

To date, the initial phase of the program has been completed with the culmination of the conceptual design for the desalination process itself and the completion of the intermediate series of tests and studies. The results of the investigations that led to the process concept design were previously documented in Metropolitan Preliminary Design *Report No. 1084, Seawater Desalination for Southern California (Report No. 1084).* The results of the intermediate tests and studies, which were conducted based on recommendations stemming from *Report No. 1084*, are documented in this summary report. This documentation includes a review of the results from the 2,000-gallon-per-day Test Unit, university research, tube fabrication analyses, and concrete testing.

A next phase of the Desalination Demonstration Program is the implementation of the seawater desalination demonstraton plant. These activities include design, construction and operation of such a plant. Additional work at the Huntington Beach Test Unit will take place to further confirm and expand upon previous testing. Documentation of this project phase will be prepared as funds are approved by the Board of Directors and as the individual tasks are implemented.

CONCEPT DESIGN OF SEAWATER DESALINATION PROCESS

The initial program phase was completed in October 1993 when Metropolitan published *Report No. 1084.* The report presented a conceptual design of a 75-MGD seawater desalination plant using vertical tube evaporation (VTE) technology in a multi-effect (multicycle) distillation process. The distillation process envisioned in this report consists of double-fluted aluminum tubes stacked in a cylindrical concrete vacuum enclosure. The VTE system uses steam heat from a coastal power plant to evaporate seawater and capture the condensate as product or potable water. The optimum number of effects in this design was determined to be 30. This means that after steam is cycled through the last of the 30 effects, all useful thermal energy from the steam heat will be completely spent. The report also contains projections of optimum performance parameters for an operational plant.

The preliminary design concept outlined in *Report No. 1084* incorporates two important innovations in material use for the VTE process. First, concrete is used as the material of construction for the distillation vacuum shell instead of the typical steel-vessel construction. Second, the VTE technology uses an aluminum alloy for the evaporator tubes instead of the customary copper-nickle alloy. *Report No. 1084* concluded that these two primary innovations represent the most significant process features affecting Metropolitan's ability to significantly reduce the costs of seawater desalination.

Despite these apparent technological advantages, *Report No. 1084* concluded that these innovations carried with them several key uncertainties. The report recommended that these uncertainties be resolved before commencing the design of a full-scale (75-MGD) plant. As documented in *Report No. 1084*, a plan to resolve these uncertainties resulted in a series of intermediate activities that included specific materials testing as well as laboratory- and pilot-scale testing of the unique process. The recommendations and phases of additional studies in *Report No. 1084*, and listed below, became the basis of the test/study program documented in this report.

- Construct and operate a small pilot-scale test unit evaporator to confirm the heat transfer performance and corrosion resistance of aluminum.
- Conduct additional desalination tests and measurements at a qualified university laboratory.
- Develop and conduct a test program to find the best concrete mix for the vacuum vessel and determine quality control guidelines for vessel construction.
- Determine fabrication techniques for aluminum tubes and tube bundles, estimate fabrication costs, and determine quality control techniques.

SUMMARY OF RESULTS FROM TEST/STUDY PROGRAM

Test Unit

Since *Report No. 1084* was issued in October 1993, Metropolitan has successfully constructed and operated a 2,000-gallon-per-day desalination Test Unit in Huntington Beach, California. The testing program developed for this experimental unit was aimed at deriving information that would assist the designers of a larger seawater desalination plant (Demonstration Plant) to specify optimum design parameters. The Test Unit, located at the Southern California Edison Company's Huntington Beach power plant, consists of two discrete testing components: a long-term test unit (LTTU) and a short-term test unit (STTU). Each component can be operated and controlled independent of the other. The LTTU is operated under fixed temperature and pressure conditions to demonstrate the long-term operational integrity of the distillation process, and to verify that the quality of the water produced by the process remains constant over time. The STTU is used to demonstrate heat transfer performance of the aluminum tube bundles under varying temperatures, pressures, and flow rates.

The objectives of the experimental program at the Test Unit were to improve the measured accuracy of heat transfer coefficients in the unit's evaporator and feedheater, determine a baseline flow rate for the product water, demonstrate that the product water can meet Title 22 drinking water quality requirements as outlined by the California Department of Health Services, and confirm that the VTE desalination process can be successfully integrated into a larger capacity Demonstration Plant. The following items document the findings of the Test Unit's experimental program to date:

- Test Unit data has been collected and the conclusions in this report are based on that data.

- The theoretical values for heat transfer coefficients of the aluminum tubes have been achieved or exceeded.
- Baseline data for the anticipated production of product water for the process has been collected.
- The Title 22 water quality tests indicate that both primary and secondary drinking water standards are met by the process.
- Successful integration and the simultaneous operation of the various components of the Test Unit have been demonstrated.
- Finally, the Test Unit has successfully served as a vehicle to verify that the original processes and components described in *Report No. 1084* will perform as expected.

Single-Tube Apparatus

A single-tube distillation test apparatus was developed and tested by the University of California at Los Angeles Department of Mechanical and Aerospace Engineering. This test apparatus was used to obtain precise heat transfer coefficients for seawater and deionized water as a function of temperature difference, pressure, and flow rate. This data was then used to extrapolate heat transfer performance for the double-fluted aluminum tube system on which the conceptual design of a full-scale desalination facility is based. The laboratory-scale tests demonstrated that, for the double-fluted aluminum tube to be used in this project, the measured values of heat transfer coefficient, driving temperature, and flow rate met or exceeded the values predicted in *Report No. 1084.*

Fabrication and Manufacturability

Tests were conducted by Reynolds Metals Company to develop a quick, economical method for joining the tubes to a tubesheet or base. Ideally the method developed would reduce sites of potential corrosion while demonstrating the strength needed to support the process, and provide for economical manufacturing techniques that use standard machine tools and processes. The results of these tests and development work conducted to date show that:

- Double- and single-fluted tubes suitable for the VTE distillation process can be extruded at competitive production volumes and costs.
- The tube-to-tubesheet connection consisting of an expanded joint with a sealant provides optimum strength, corrosion resistance, and ease of manufacture.

- Current manufacturing techniques and existing machine tools can satisfy the quality control requirements specified for tube bundles and feedheater tubes.

Concrete Compatibility Tests

Report No. 1084 initially determined that concrete was the best construction material for the vacuum containment shell because of its superior impermeability, corrosion resistance, and low cost. In addition, recent developments in concrete additives allow for the development of concrete mixes to suit project-specific requirements. The full-scale desalination plant design identified in *Report No. 1084* requires strength, workability, impermeability, and durability. Metropolitan conducted tests of both traditional concrete mixes and concrete mixes containing specialized additives. These tests indicate very promising performance characteristics for concrete including:

- A concrete mix can be readily prepared that exhibits the compressive strength and workability required for slip-form wall construction.
- The permeability and durability of the specialized concrete mix makes it an excellent candidate for use in the environment that will exist in a vacuum containment vessel.

CHAPTER 2
PROCESS DESCRIPTION: A SHORT REVIEW

Figure 2-1 shows the process concept for a full-scale desalination plant appears in simplified form. By collocating the desalination plant at the site of a coastal power plant, the desalination process can take advantage of low pressure steam available from the power plant. This steam is used as a heat source to evaporate seawater drawn from the plant's existing seawater cooling system.

As shown in Figures 2-1 and 2-2, the incoming seawater is pumped to the top of the distillation process so that it can flow by gravity downward through a series of aluminum

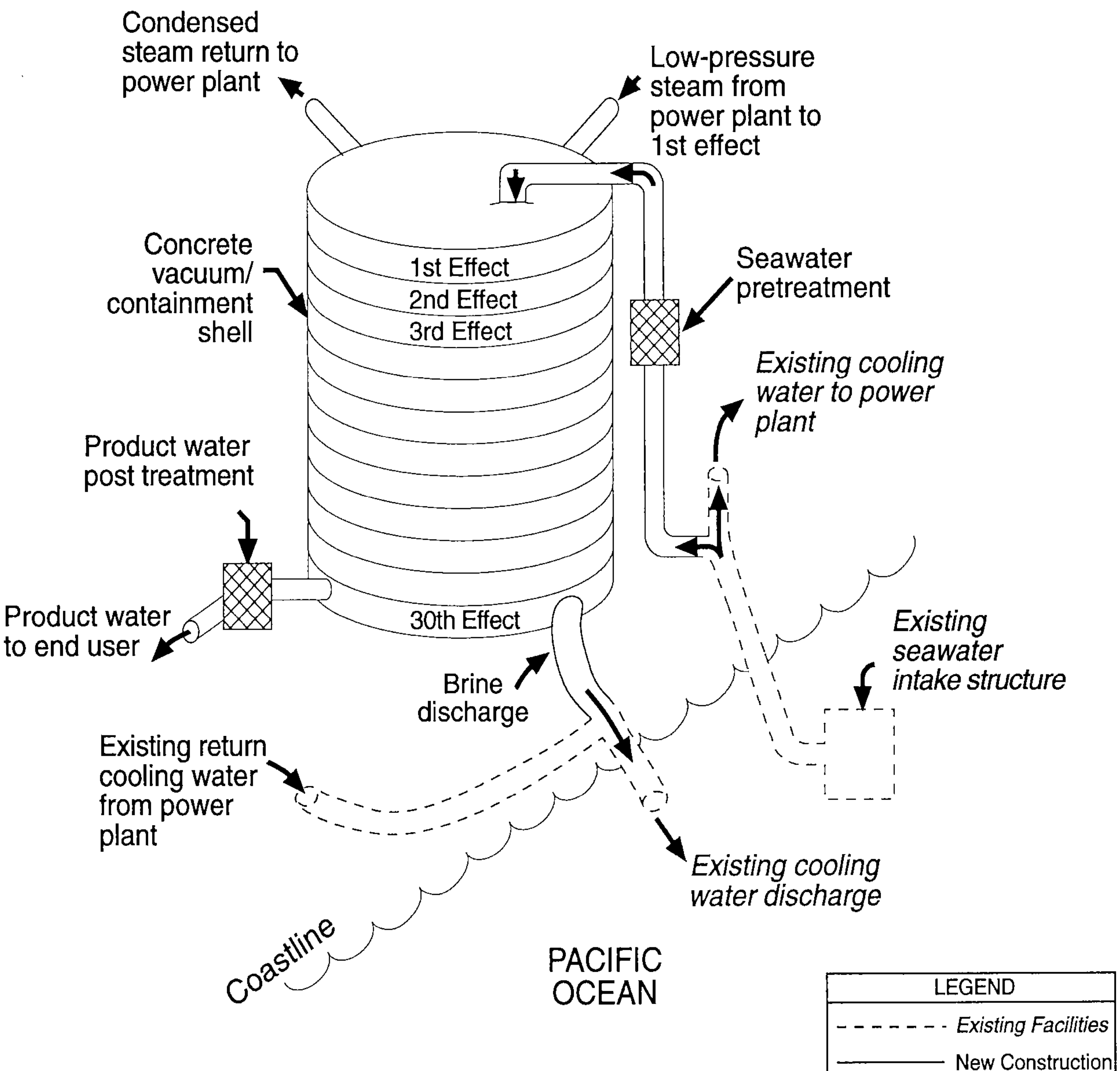


Figure 2-1 - Major features of a full-scale vertical tube evaporation desalination plant

tubes. As the water flows down the inside of each tube, it is exposed to low pressure steam heat circulating around the outside of the tubes. This steam heat causes a portion of the seawater to evaporate into steam which later condenses as potable or product water in succeeding effects. In the conceptual design, the process is repeated as many as 30 times until all usable thermal energy has been extracted from the steam. At the bottom of the last effect, the remaining seawater (or brine), which has a heavier concentration of salts than natural seawater, is discharged into the ocean.

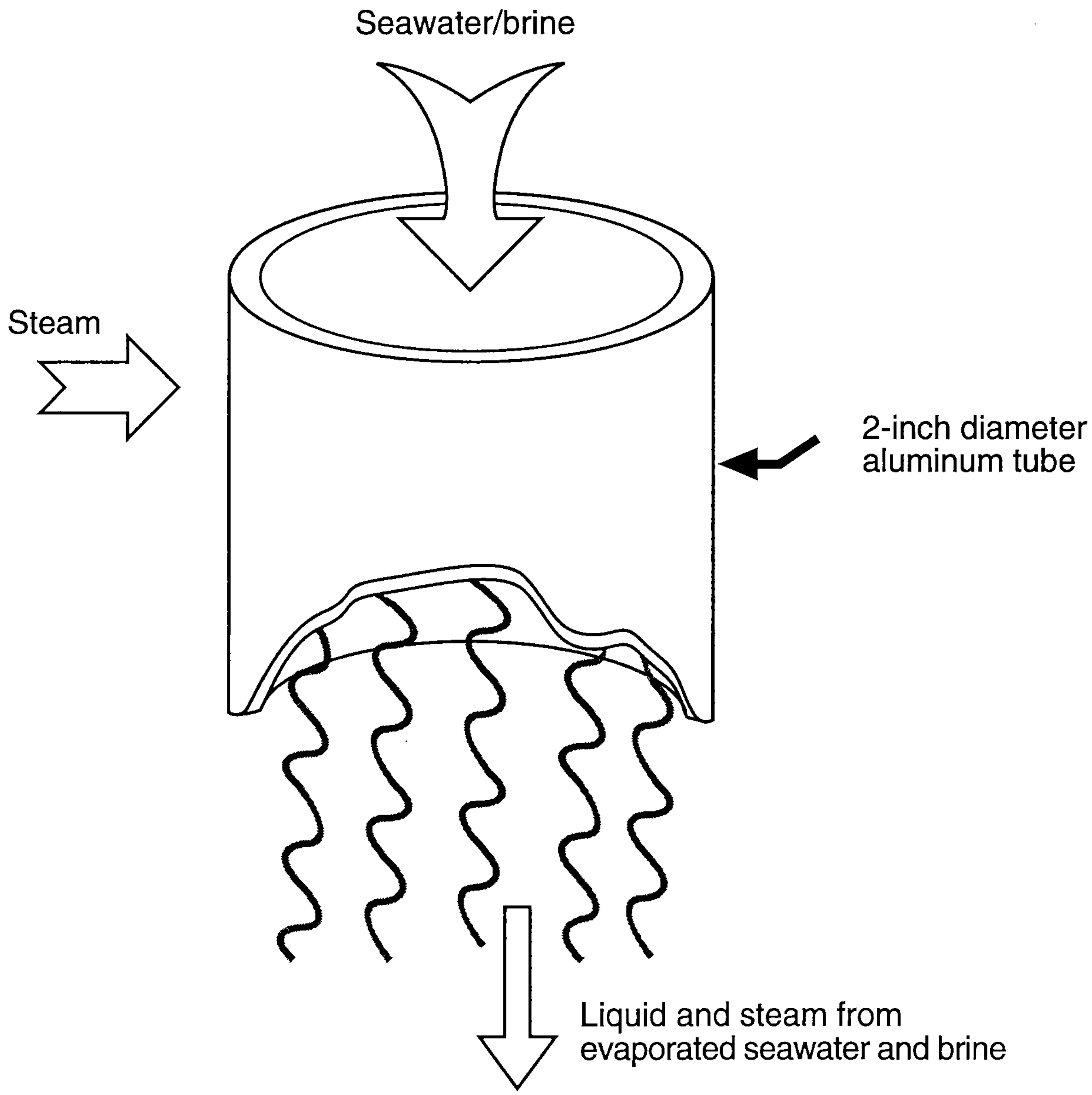


Figure 2-2 - Basic evaporative process for a single tube

The core component of the process is the distillation tube bundle that evaporates seawater and condenses vapor to produce product water. Each effect consists of an apparatus that distributes incoming seawater/brine, a tube bundle which serves as the sites for the evaporation process, and a plenum chamber at the bottom of the tube bundle that collects product water and directs brine to the succeeding tube bundle. Each tube bundle is composed of numerous fluted tubes. The tube ends are individually attached to tubesheets which align and hold the tube array in place. A typical tube bundle in the fabrication stage is shown in Figure 2-3.

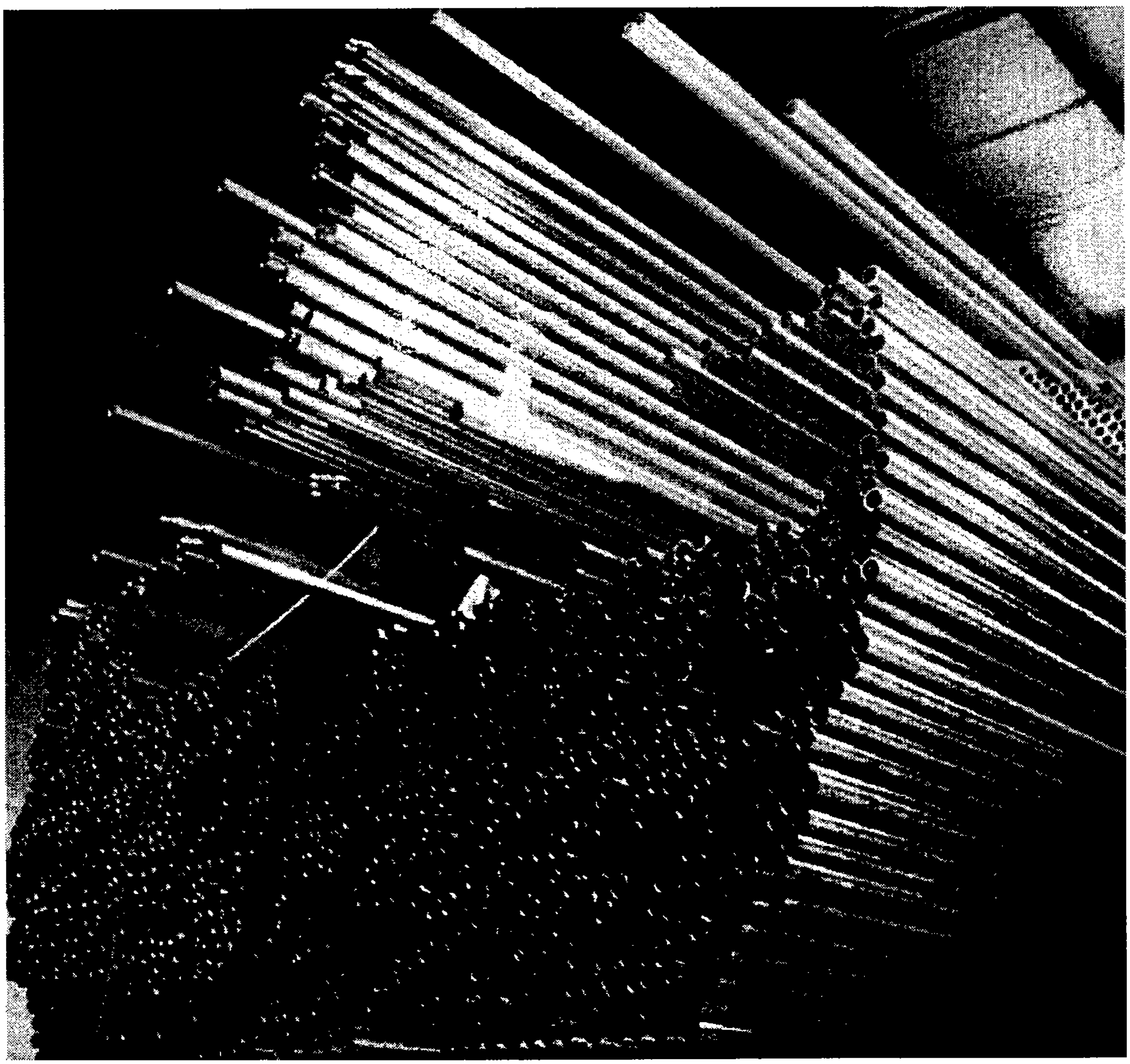


Figure 2-3 - Typical aluminum tube bundles during fabrication

In the 1960s, VTE technology was developed as a potential desalinated water production process under the aegis of the U.S. Department of Energy's Office of Saline Water. This effort was an attempt to achieve high heat transfer rates and low temperature differentials by using thin-film evaporation and condensation and by providing tube surfaces that enhanced the heat transfer process.

The VTE concept was tested extensively and proved successful and stable at several small-scale demonstration plants. However, several early large-capacity commercial plants did not meet performance and reliability expectations. These large plants were generally built with low budgets, and used inferior equipment and materials, both of which were later diagnosed as major contributors to their failures. Today, single- and multiple-effect VTE systems are used extensively in the chemical process industries; however, those applications do not include desalting seawater.

The use of the vertical tube evaporation process to produce potable water from seawater is particularly well suited for parallel operation with a coastal power plant. The desalination process readily lends itself to economical operation at steam supply temperatures as low as 165°F, typical of the steam quality available from such power plants. In addition, the proximity of the plant's seawater intake and outfall provides for a convenient supply of water to the process and easy disposal of the brine from the VTE process.

VTE systems also show excellent heat transfer performance because of the condensation/evaporation heat transfer process in each effect. The novel use of double-fluted tubes in Metropolitan's design enhances both surface area and heat transfer. Another enhancement is the use of aluminum as the material for the tube bundles. Aluminum allows additional improvements in material heat transfer properties as well as much lower construction costs.

CHAPTER 3
HUNTINGTON BEACH TEST UNIT

In November of 1991, the Metropolitan Board of Directors authorized the design and construction of a pilot-scale, 2,000-gallon-per-day Test Unit to verify conceptual design features before approving funds for the final design of a larger Demonstration Plant. The 2,000-gallon-per-day Test Unit was designed by Metropolitan engineering staff. Reynolds Metals provided the unit's vertical tube bundles. Metropolitan's staff fabricated the remaining Test Unit components at its facilities in La Verne. The Test Unit design consists of individual components identical to the Demonstration Plant. All components were then transported to Southern California Edison's (SCE) power plant in Huntington Beach for final assembly. Metropolitan completed assembly of the Test Unit during the summer of 1995, and the testing program has been under way since that time.

The Test Unit provides an experimental platform for demonstrating major test program objectives and functions as a design and development tool to assist in establishing design details and specifications for the Demonstration Plant.

Figure 3-1 shows the basic components of the Test Unit and Figure 3-2 shows the unit in place at the SCE Huntington Beach power plant. A seawater supply pump was installed at the cooling water source to the SCE power plant. Pretreatment systems upstream of the distillation process remove scale precursors, control the seawater pH, strip out excess oxygen, and filter out sediments suspended in the seawater. Heat energy in the form of steam is supplied to the distillation effects from the power plant's existing auxiliary steam supply system.

The Test Unit actually consists of two complete experimental plants: a long-term test unit (LTTU) and a short-term test unit (STTU). Each plant consists of two vertical-tube evaporating effects constructed of 10 tubes, each 2 inches in diameter and 4 feet long. As the incoming seawater enters the evaporator and flows in a thin film down the inside of each tube, power plant steam flowing past the outside of the tube evaporates a portion of the seawater. This evaporation process produces a mixture of steam and brine. The vapor produced in the top distillation effect becomes the heat source for the bottom effect. The vapor is condensed in the second effect to produce desalinated or product water. Process water moves in sequence from the top effect to the next effect below, until the lowest effect is reached. The Demonstration Plant will be composed of 30 vertical evaporating effects.

The LTTU is physically identical to the STTU; however, it is designed to operate under a relatively fixed set of temperature and pressure conditions to demonstrate the long-term operational integrity of the process. The LTTU operates at high-end temperature conditions to verify aluminum performance at the worst-case conditions for scale buildup. Prod-

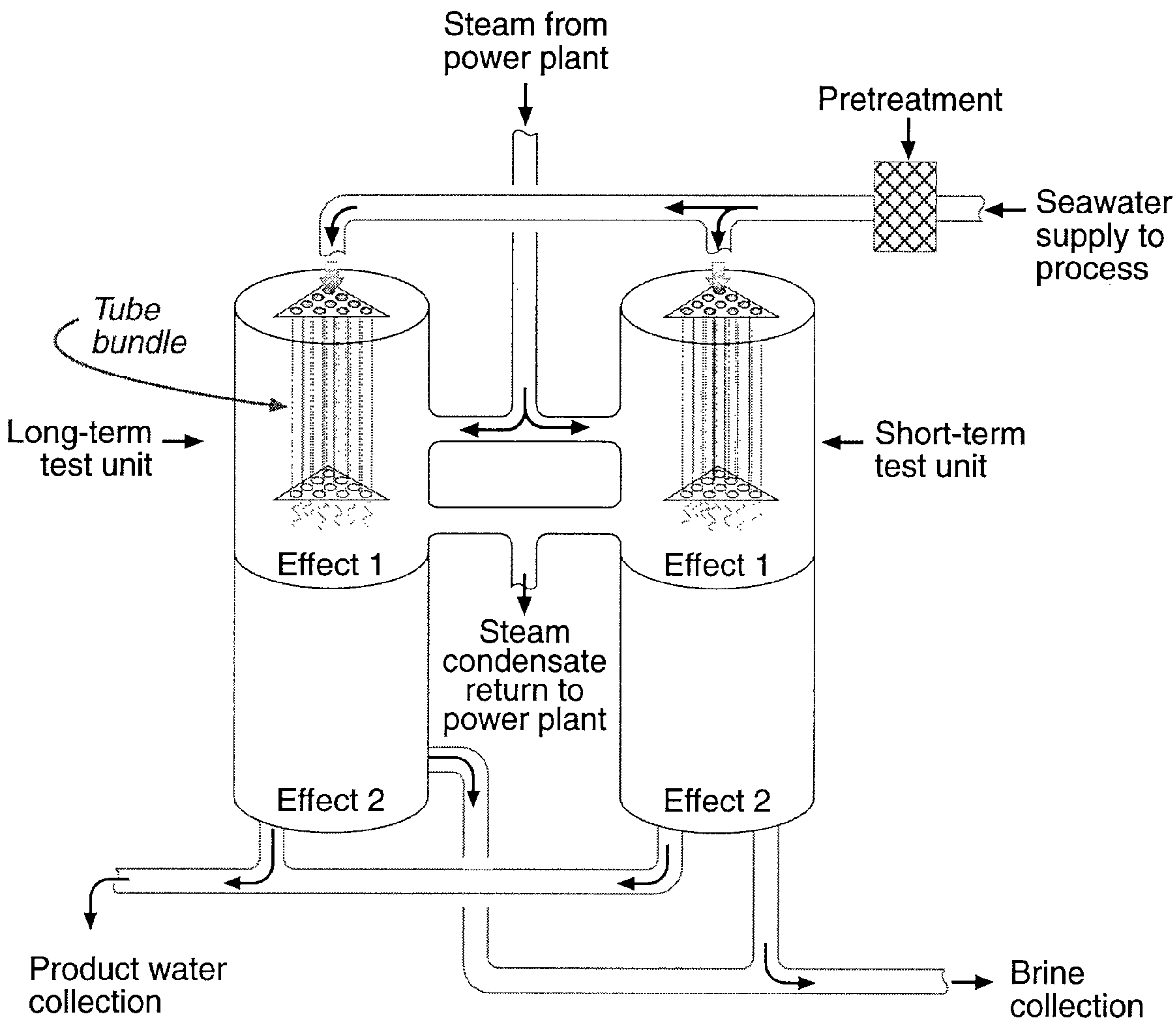


Figure 3-1 - Process schematic of Huntington Beach Test Unit

uct water from the LTTU provides samples for water quality testing. The STTU is equipped with additional controls and instruments and is used to measure heat transfer rates across the entire range of operating temperatures. The unit provides the operating conditions that allow any two successive effects in a 30-effects plant to be replicated. With the additional instrumentation, the heat transfer performance of the aluminum tube bundles can be measured under a variety of operating conditions.

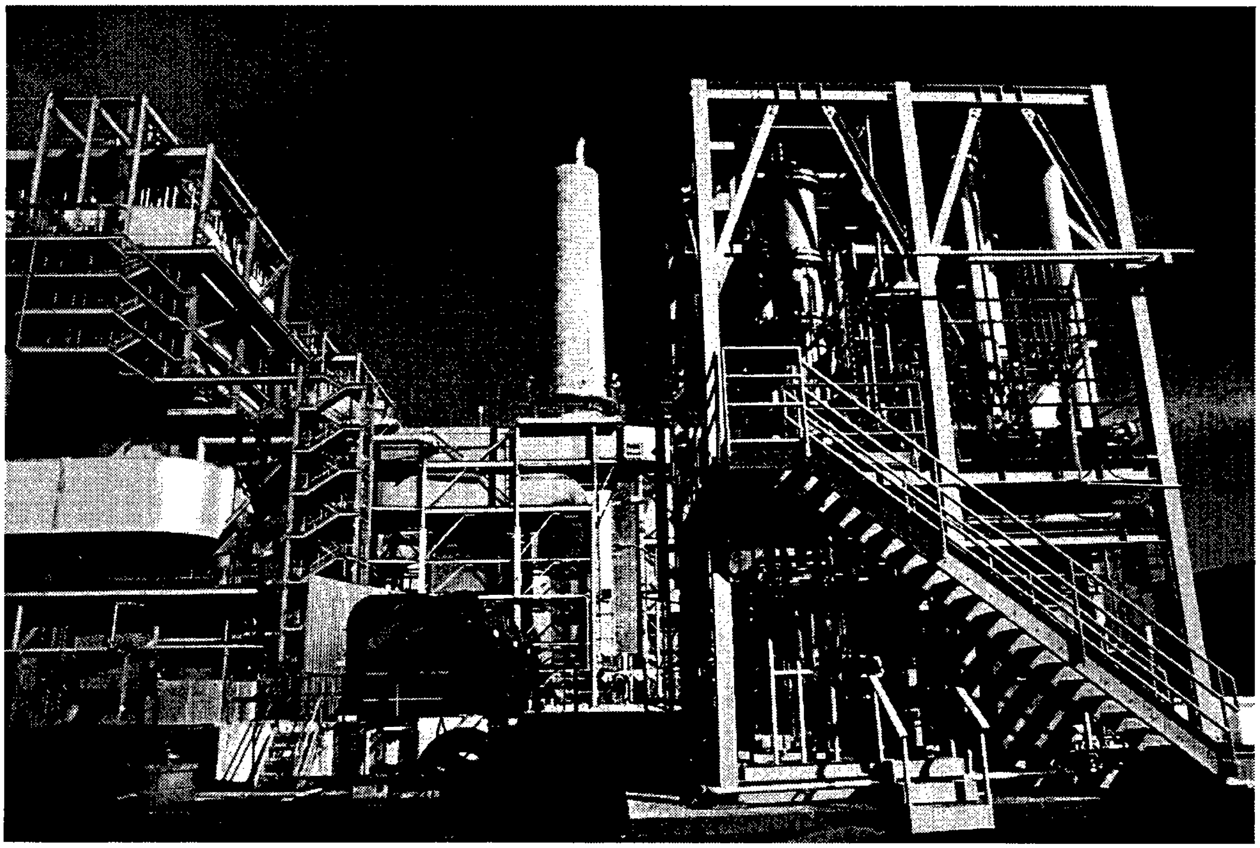


Figure 3-2 - Test unit (at right) in place at Huntington Beach with SCE power plant in background

TEST OBJECTIVES AND RESULTS

Five objectives were developed for the Test Unit, and each is discussed below.

Heat Transfer Coefficients—Evaporator Tubes

The first objective of the Test Unit program was to accurately measure heat transfer rates, *U*, in the evaporator tubes. Experimental validation of heat transfer coefficients and reducing the band of uncertainty around the actual value will create a basis for final design criteria for the most economical use of aluminum tubing, thereby reducing project costs. All experimental measurements were collected once the STTU had achieved an equilibrium condition.

The following evaluation criteria developed by scientists and consultants for Metropolitan were used to assess whether the heat transfer performance of the evaporator tube bundles was successfully achieved. These criteria and test results include:

- Measured heat transfer is within ±10 percent of heat transfer performance set forth in *Report No. 1084.*
- Measured heat transfer rates are repeatable within 15 percent.

Heat Transfer Coefficients—Feedheater Tube

The second objective of the Test Unit program was to measure heat transfer rates, *U*, in a feedheater tube. These tests were intended to determine the heat transfer rate of a single feedheater tube at the anticipated feed water temperature levels of the evaporation tubes. The test requirements were the same as for the evaporator tubes.

Evaluation criteria to be used to assess whether the second objective was successfully achieved include:

- Measured heat transfer is within ±10 percent of the heat transfer performance projected in *Report No. 1084.*
- Measured heat transfer is repeatable within 15 percent.

The heat transfer coefficient measurements for the feedheater tube have been delayed to complete the initial evaporator testing. The results of these tests will become available at the conclusion of the testing program.

Baseline Water Production

The third objective involved gathering process data to document a baseline flow rate for water produced per linear foot of tube. Water production is directly linked to the evaporator tube's heat transfer performance. Establishing this database has two benefits. First, as potential design variations are developed and evaluated in the Test Unit, production values can be compared to the baseline data for qualitative assessments of the impact of any potential design change. Second, a base of information can be established for expected water production in the Demonstration Plant.

With the STTU operating under a variety of conditions, measurements were taken to document the amount of water produced. The sole purpose of this test was to gather baseline data for future comparisons.

The quantity of product water varies with the operating temperature and the temperature difference across the evaporator. As heat transfer coefficient tests are conducted, the respective quantities of product water are recorded. The accumulated results of these production quantities will establish the base of information about water production values. Current data ranges from a maximum of 200 percent of design value to a minimum of 31 percent of design value. Data collection in this area is scheduled to continue.

Water Quality Testing

The fourth objective was to demonstrate that the product water produced by the 2,000-gallon-per-day Test Unit met Title 22 drinking water requirements as directed by the California Department of Health Services. Two separate Title 22 tests were planned with samples taken from the LTTU: one sample at the early stage of operation and the second in the later stages of operation. This objective was to be considered successfully achieved if all primary and secondary drinking water standards were met. In addition, daily samples of product water were tested for levels of aluminum to obtain process material performance information.

Title 22 samples were taken from the LTTU on May 2, 1996. Test results showed no product water constituents, including aluminum, in excess of Title 22 requirements. This data shows that Title 22 requirements have been met.

Aluminum concentrations in the product water became a concern when initial water quality tests in October 1995 showed that aluminum levels exceeded the secondary standard of 200 parts per billion (ppb). Additional testing conducted the following month showed aluminum levels below 200 ppb. Metropolitan staff believe that the aluminum levels in the product water were lower in November because of the 24-hour operation of the Test Unit. Under continuous operation, a protective oxide layer will form on the aluminum tubes. In March 1996, after several changes in plant operation, aluminum levels in the product water were measured at 10 to 15 ppb. These levels demonstrate the integrity of the heat transfer materials and are well below the secondary standard of 200 ppb.

Process Operations

The fifth objective was to achieve continuous, steady-state operation of the distillation process over a sustained period. Such operation would also demonstrate that an assembly of individual processes can be successfully integrated into a single treatment operation. The LTTU is being operated to show that the Test Unit processes—the essential process components of the Demonstration Plant—can be operated as an integrated whole. The critical process units to be integrated are:

- The seawater intake system
- The pretreatment chemical and process units
- The vertically-stacked, multi-effect evaporative process using fluted aluminum tubes

All these units are being operated at the temperatures, pressures, and concentrations planned for the Demonstration Plant. Process integration was to be deemed successful when the plant controls maintained a steady-state operation, day after day.

Since February 1996 the LTTU has been operated continuously over extended periods. During this time all component systems were in operation, and the pretreatment process, acid feed, and decarbonator were all successfully operated. Also during this period, the two-effect LTTU yielded product water that was tested for Title 22 water quality requirements. The successful, simultaneous operation of all these components means that this objective has been met.

CONCLUSIONS

- The expected values for heat transfer coefficients for the evaporator tubes have been measured. Test results exceed the levels originally outlined in *Report No. 1084*.
- The heat transfer coefficients for the feedheater tubes will be measured when the tests for the evaporator tubes have been concluded.
- Results of the Title 22 product water quality tests show that drinking water quality standards can be met.
- Successful integration and simultaneous operation of the critical Test Unit components has been demonstrated.

CHAPTER 4
SINGLE-TUBE TEST PROGRAM

BACKGROUND

In the summer of 1992, the University of California at Los Angeles (UCLA) Department of Mechanical and Aerospace Engineering was added to Metropolitan's desalination test program team. UCLA's scope of work included the fabrication and testing of a single-tube test apparatus consisting of a 4-foot-long, 2-inch-diameter aluminum evaporator tube. The purpose of this single-tube apparatus was to obtain precise heat transfer coefficient measurements. The test apparatus was designed so that it could be quickly modified to permit tests of various tube profiles and to allow microscopic examination of tube surfaces. In addition, the apparatus allowed for variations in other process-related parameters by providing quick results and feedback on system performance. Figure 4-1 is a simplified diagram of the test apparatus, and a photograph of the unit appears in Figure 4-2.

UCLA completed the fabrication of the single-tube apparatus in October 1993 and soon thereafter conducted experimental tests. Both deionized water and seawater were tested in this closed-loop unit. Except for the expected differences in boiling points, no appreciable difference was measured in the heat transfer coefficients for the two liquids. Preliminary data for overall heat transfer coefficients at various temperatures, pressures, and flow conditions were obtained for deionized water only. Later, the single-tube apparatus was refurbished, the earlier data sets were confirmed, and further testing was conducted to include a wider range of system parameters.

TEST OBJECTIVES AND RESULTS

The primary objective of UCLA's single-tube test program was to determine the heat transfer coefficient for a single, 4-foot-long, 2-inch-diameter, double-fluted vertical aluminum tube. The heat transfer coefficient was determined as a function of temperature differential, pressure, and flow through the single tube. The range of operating parameters matched those defined in *Report No. 1084*. The experimental verification of the theoretical heat transfer coefficients in the single-tube test apparatus provided empirical validation of the theoretical values. With the increased confidence in the heat transfer characterization, greater confidence was established in the projected volumes of product water for the Demonstration Plant.

The test apparatus (Figure 4-1 and 4-2) was designed to duplicate the thermodynamic and hydrodynamic conditions of a full-scale, multi-effect VTE desalination system that uses condensing steam to evaporate saturated brine flowing down vertical tubes. As brine flows down the inner walls of a tube, it is evaporated by heat transferred across the exterior wall of the tube from the condensing steam. By measuring the volume of the condensate

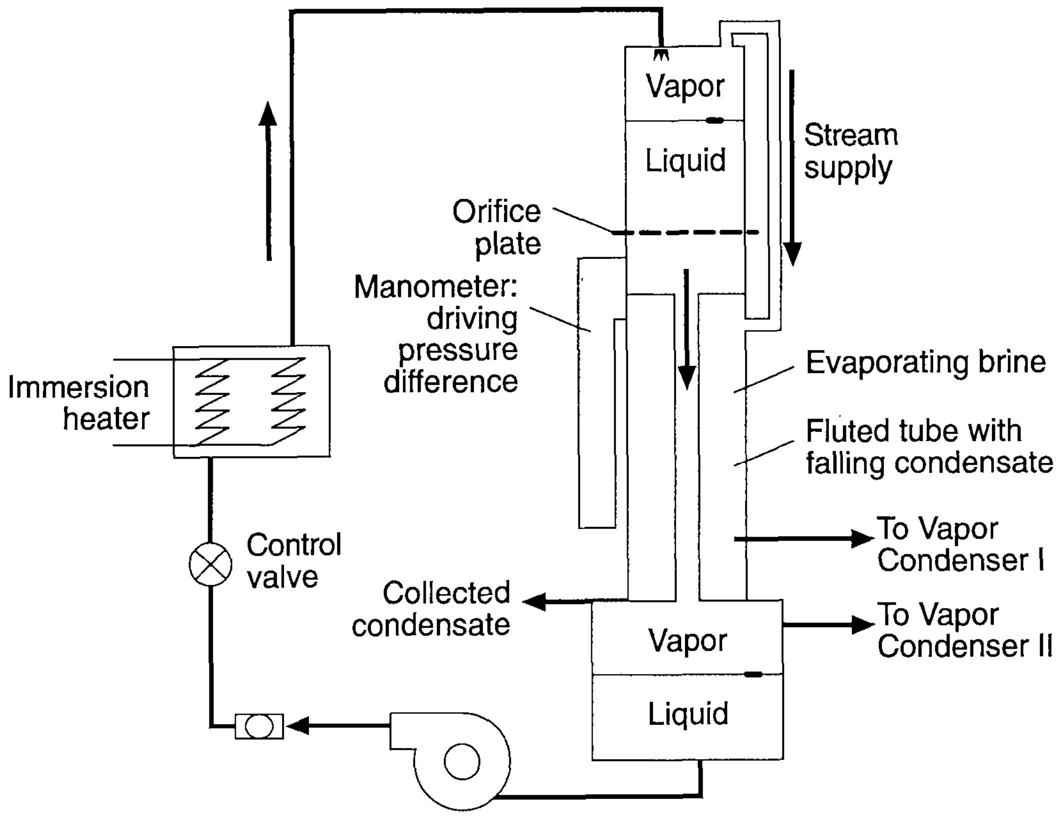


Figure 4-1 - Process schematic of single tube test apparatus

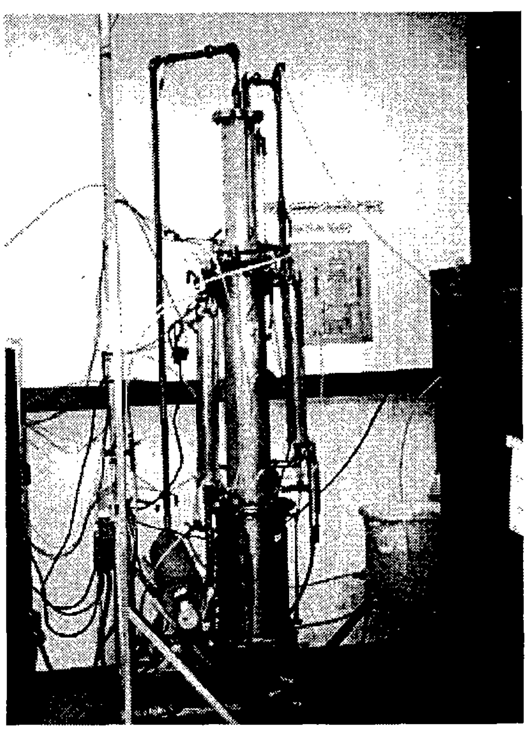


Figure 4-2 - Single tube test apparatus set-up at UCLA

thus produced, the geometry of the tube, and the differences in temperature and pressure, the overall heat transfer coefficient, *U*, for a tube can be calculated. The single-tube apparatus was designed to operate at temperatures of 100 to 230°F and pressures of 0.95 to 20.8 pounds-per-square-inch-absolute (psia). Brine flow rates were varied from 0.5 to 3.0 gpm for each operating temperature. The single-tube tests were to be considered successful if they produced repeatable heat transfer coefficient measurements within approximately 10 percent of the heat transfer perfromance figure projected in *Report No. 1084*.

Tests were conducted at UCLA using both deionized water and saltwater as feedwater to the test apparatus. Initial tests were conducted at temperatures ranging from 120 to 200°F. During these tests the driving temperature differences ranged from 1.5 to 5.5°F and water flow rates in a single tube ranged from 0.8 to 1.5 gpm. During these tests the differences in the heat transfer coefficients for the two liquids were determined to be negligible.

Additional tests were conducted to confirm the initial results and to extend the range of water flow rates through the tube. The results of all tests are summarized in Figures 4-3a and 4-3b. The average heat flux, *q*, across the tube is shown in Figure 4-3a as a function of driving temperature difference for the full range of flow rates and brine temperatures. In Figure 4-3b, *q* is shown as a function of flow rate for constant brine temperatures and driving temperature differences. The data in Figures 4-3a and 5-3b was collected to calculate the results shown in Figure 4-3c.

The data presented in Figures 4-3a through 4-3c was successfully correlated using standard regression techniques so that *q* could be calculated as a function of brine temperature, driving temperature difference, and brine flow rate. This always showed that all data was within 20 percent of the calculated values. Additionally, the root mean square error of the average heat flux is less than 10 percent, which indicates very good correlation between the data.

The correlation data was then used to evaluate *q* for several of the design conditions presented in *Report No. 1084*. The heat transfer coefficient, *U*, was obtained by taking the ratio of *q* over the driving temperature difference. The calculated heat transfer coefficients and their estimated errors are shown in Figure 4-3c, along with the design curve. Predicted results, based on the correlation of observed results, show excellent agreement with the predicted curve in *Report No. 1084*.

UCLA also performed an abbreviated series of tests using a laboratory prepared sample of saltwater. Those test results are shown in Figure 4-4 as a function of driving temperature difference. The saltwater data was obtained at a brine temperature of approximately

CHAPTER 5
FABRICATION TEST PROGRAM

BACKGROUND

During the 1960s, Reynolds Metals Company (Reynolds), under the direction of the Department of Energy Office of Saline Water, built and operated an aluminum-tube desalting plant at Wrightsville Beach, North Carolina. This demonstration plant operated from June 1968 to February 1973. Initially, the plant featured a multistage flash distillation process. The plant was later modified by adding three all-aluminum vertical tube effects using 2-inch-diameter tubes. The primary objective of this project was to evaluate the suitability of candidate aluminum alloys for use in seawater desalination systems. This test effort resulted in the conclusion that certain magnesium-containing aluminum alloys were compatible with the hot brine present during the seawater distillation process.

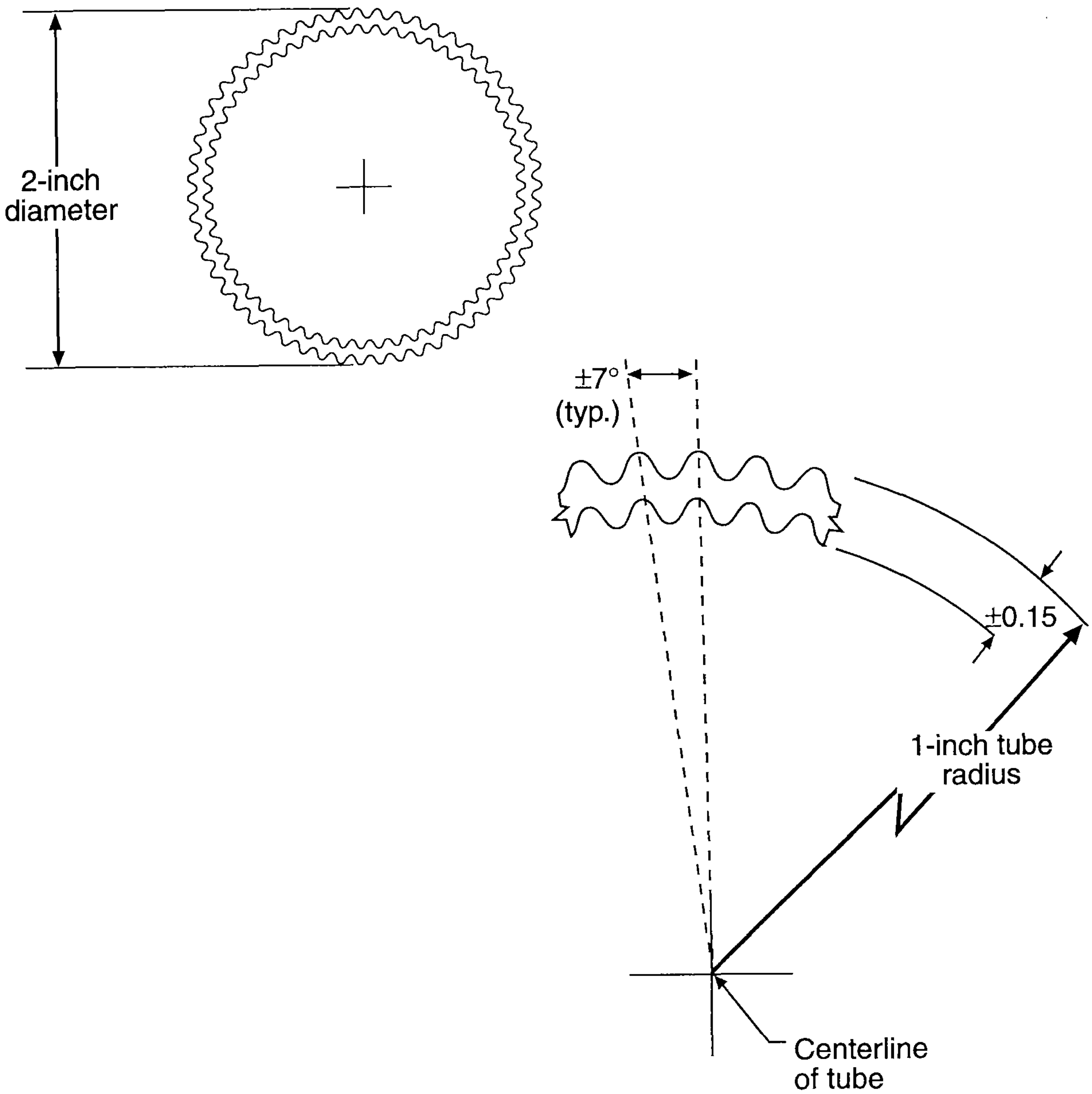
As a result of the positive experience at Wrightsville Beach, Reynolds was included in Metropolitan's desalination program. Reynolds' scope of work on the project encompassed three objectives: (1) design the fluted evaporator tube, (2) determine whether large quantities of the fluted aluminum tubes for the Demonstration Plant could be extruded successfully and economically, and (3) determine whether the tube bundles could be manufactured to specification at a reasonable cost. This latter objective included determining quick and cost-effective methods for joining the tubes to the tubesheets.

TEST OBJECTIVES AND RESULTS

Design of Aluminum Tubes

The first objective of this fabrication program was to design and produce aluminum tubes for the test unit evaporator and feedheater. For the evaporator, two profiles of extruded 2-inch-diameter double-fluted tubes were produced and tested, and a single profile of 3/4-inch-diameter single-fluted tube was provided and tested for the feedheater. The goal of these efforts was to determine whether double-fluted tubes could be produced in a cost-competitive manner using conventional manufacturing equipment and techniques. Fluted tubes were selected as the best candidates for evaluation because of the desalination process advantages that resulted from the tube's superior heat transfer geometry. Figure 5-1 shows a cross-section and detail of the evaporator fluted tube used in the Reynolds test unit.

Aluminum billets of alloy MG375, developed from Reynolds' experience at Wrightsville Beach, were produced and extruded into the desired shapes. Reynolds used standard manufacturing equipment and processes to project manufacturing costs for large orders of these innovative tubes. The double-fluted tubes were successfully extruded and the projected costs for producing large quantities were found to be competitive with costs for similar aluminum extrusion products.



Note: All dimensions are in inches unless otherwise shown.

Figure 5-1- Cross-section of a double-fluted aluminum tube

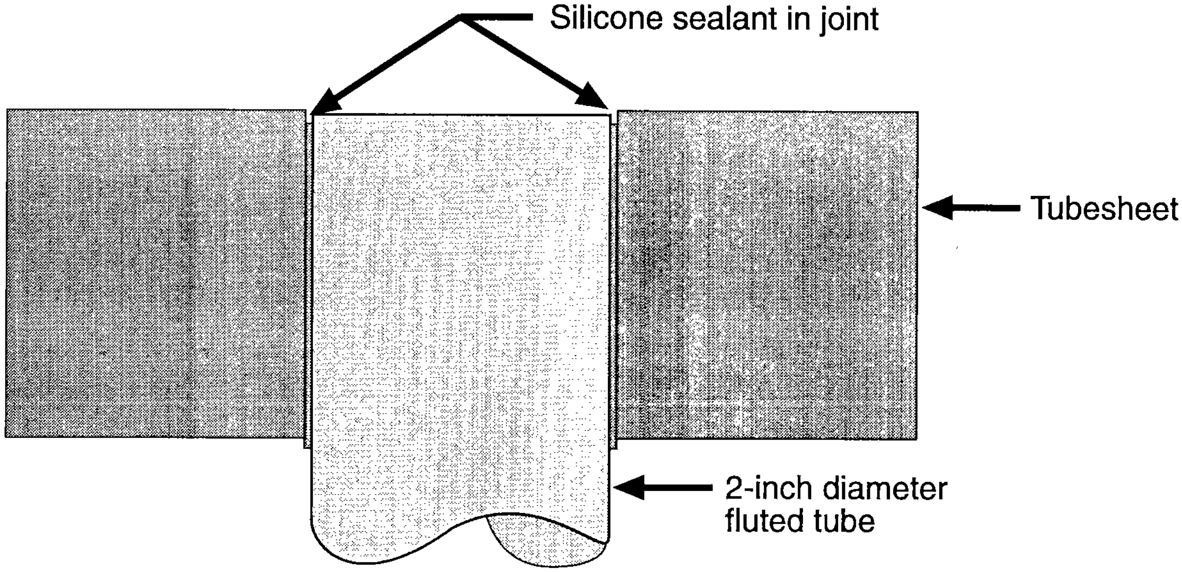


Figure 5-2 - Recommended tube-to-tubesheet joint

Tube-to-Tubesheet Joining Method

The individual tubes are aligned and held in place with tubesheets located at either end of the tubes. The use of double-fluted tubes presented uncertainties as to how the tube would be attached to the tubesheet. Therefore, the second objective of the fabrication program was to test and develop methods for joining 2-inch-diameter fluted tubes to an aluminum tubesheet. A successful joining method had to be rapid, economical, and highly reliable, and produce a tube-to-tubesheet joint free of crevices that could act as sites for corrosion cells in an operating plant. Figure 5-2 shows the recommended tube-to-tubesheet connection.

Finite element analysis conducted by Reynolds concluded that the optimum thickness for a tubesheet was one inch. Reynolds investigated a number of techniques for joining tubes to the tubesheets, including welding, magneforming, explosive bonding, adhesive bonding, expanding, and expanding with an adhesive or sealant. Several joints were selected and evaluated in corrosion tests, pressure tests, and tensile (pull-out) tests. Reynolds determined that a minimum pull-out strength of 100 pounds was deemed necessary for the tube-to-tubesheet joint. The major load on the joint was determined to be the dead load weight of the bundle assembly, approximately 10 pounds per tube.

The method of joining the tubes to the tubesheet (Figure 5-2) was a primary concern because of the joint's potential to become a focal point for accelerated corrosion. Reynolds conducted salt spray and boiling saltwater tests to evaluate the performance of selected joints under these environmental conditions. The results of these tests, which yielded a process patent for Reynolds, can be summarized as follows:

- The optimum joining process from the perspective of strength, corrosion resistance, and ease of manufacture was a combination of an expanded joint with a sealant. Figure 5-3 shows how the sealant is applied to the outer fluted surface of the tube, and Figure 5-4 shows the process for rolling the tube into the tubesheet to create a strong, sealed joint.

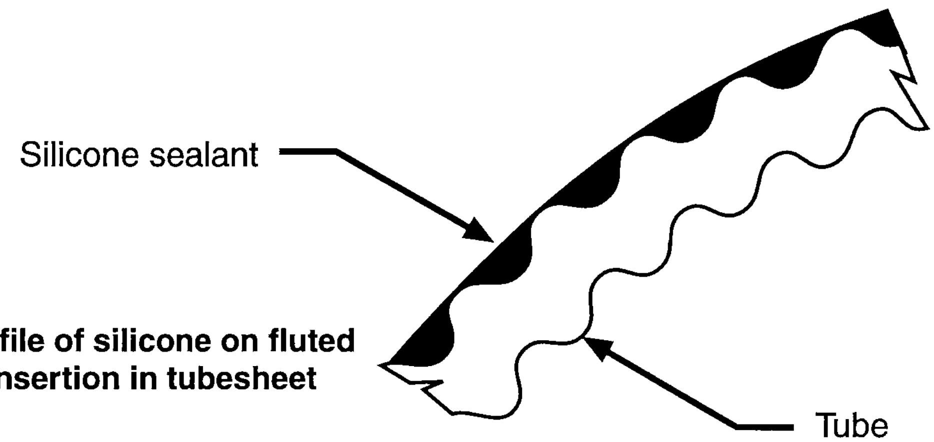


Figure 5-3 - Profile of silicone on fluted tube before insertion in tubesheet

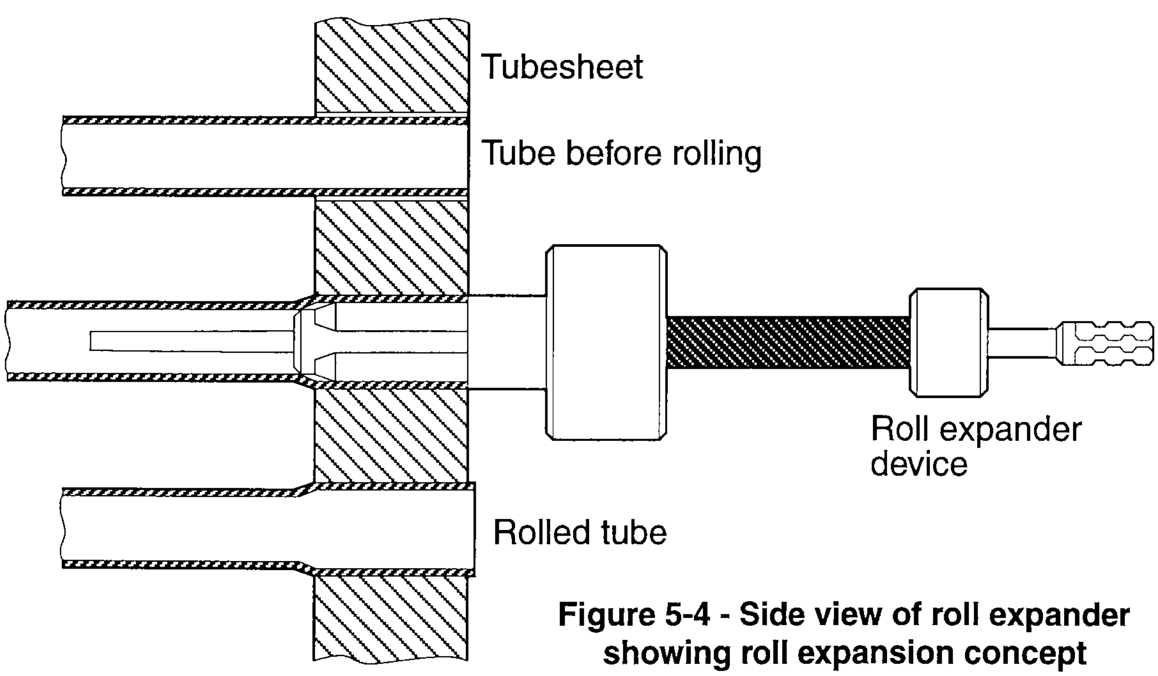


Figure 5-4 - Side view of roll expander showing roll expansion concept

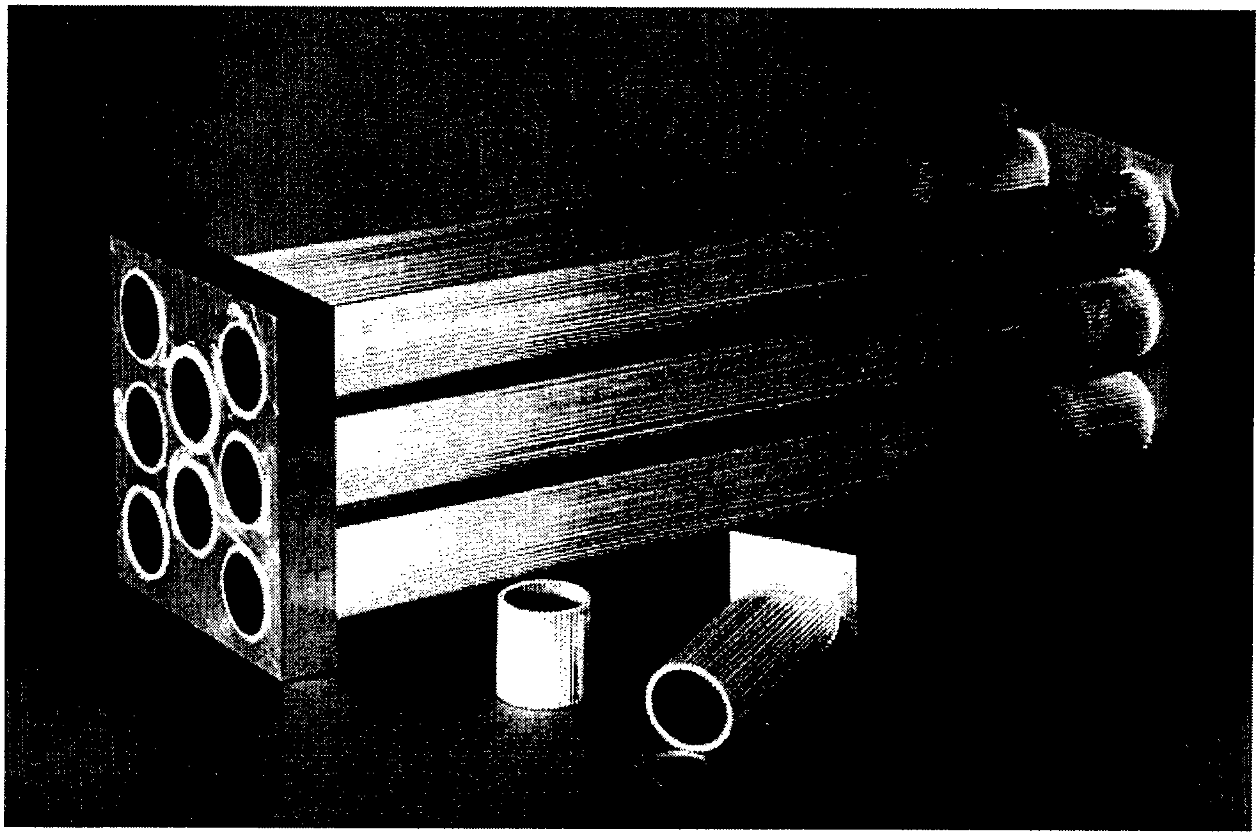


Figure 5-5 - Finished, sealed tube-to-tubesheet connections

- Joint pull-out strengths above 7,000 pounds were measured with the optimized joint configuration, which easily surpassed the minimum requirement of 100 pounds.
- Pressure failure of the joints occurred at a minimum pressure differential of 450 psi, providing a substantial margin of safety over the expected operating pressure differential of 2 to 3 psi.
- The use of an etching/coating process provided satisfactory protection from crevice corrosion at tube-to-tubesheet joints. Figure 5-5 shows the finished tube-to-tubesheet connections.

Manufacturing Techniques

The third objective of the fabrication program was to develop and test manufacturing techniques to meet equipment and material specifications for the tube bundles expected for the Demonstration Plant. This effort included the use of test jigs and fixtures and established a basic approach to manufacturing large quantities of tube bundles that met quality control requirements. Through this work, Reynolds concluded that tube bundles can be economically manufactured, at specified quality levels, using techniques and capabilities already in use in the automotive and aerospace industries.

CONCLUSIONS

- The double- and single-fluted tubes required for the VTE desalination process can be extruded at production volumes. The resulting production costs are competitive with those for other extruded aluminum products.
- A tube-to-tubesheet connection, consisting of an expanded joint with sealant, is the optimum joint to ensure strength, corrosion resistance, and ease of manufacture.
- Current manufacturing techniques and machine tools can satisfy the quality control specifications for the tube bundles and feedheater tubes.

CHAPTER 6
CONCRETE TEST PROGRAM

BACKGROUND

The use of a concrete structure as a vacuum containment vessel for the desalination process is one of the most promising innovations in the Demonstration Plant. The use of concrete is expected to result in a significant savings in both initial capital costs and annual operating costs. Typically, containment vessels for similar applications are of steel construction. However, the use of steel in Metropolitan's design would create a severe and unacceptable corrosion potential. Furthermore, the use of a steel containment vessel would be much more costly than the concrete alternative.

For these reasons, Metropolitan identified concrete as the preferred construction material during the initial conceptual stage of this program, and began a concrete testing program to determine the concrete mix and materials for use in a vacuum containment shell. The concrete's properties must provide sufficient impermeability, strength and workability, and be extremely durable in a distillation environment.

A literature search by Metropolitan showed that the Office of Saline Water had conducted substantial concrete material investigations during the 1960s. Research in Japan expanded on these investigations in the 1970s. The Japanese effort culminated in the construction of a prototype plant in 1975. Tests on this plant showed that high-quality concrete resists hot brine corrosion with no significant deterioration. In addition, the physical properties of concrete present no major obstacles to plant operation or reliability. Most important, these tests showed that acceptable concrete permeability could be achieved and that small, shallow cracks of uniform distribution caused by rapid heating/cooldown did not adversely affect airtightness or durability. The cumulative results of these literature investigations showed that concrete was a viable material for use in distillation vacuum containment shells.

Given the encouraging results of the literature search, Metropolitan concluded that the potential of concrete for use in containment structures deserved further investigation. Since permeability is so critical to the performance of the containment shell, testing was conducted to optimize the concrete's strength and workability versus the permeability of current additive mixes. Many advances in concrete technology occurred between 1975 and 1990; in particular, the development of additives that give special characteristics to concrete mixes. Consequently, Metropolitan undertook an extensive concrete testing program related to desalination applications which incorporated many of these technological advances.

TEST OBJECTIVES AND RESULTS

Concrete Mix Specifications

The first objective of the concrete compatibility test program was to develop specifications for a concrete mix. The desalination process characteristics required that the concrete be capable of achieving the requisite permeability, compressive strength, and workability. The overriding performance characteristic for concrete in a vacuum containment shell was extremely low permeability. This requirement was important since pressure losses from the process side of the structure to atmosphere must be minimized. Thus, the concrete design developed by Metropolitan must result in a finished structure with known permeability and performance characteristics. In addition, specific structural strength and workability characteristics were needed for construction purposes. Two types of tests were developed to accomplish this objective.

The first series of tests involved standard concrete batch testing on traditional mixes to establish design strengths and mix workability. Various additives were used to decrease the permeability of selected mixes. These batches were then tested using standard ASTM tests for compressive strength and workability. The tests were focused on obtaining a concrete mix composition with compressive strengths ranging from 8,000 to 10,000 psi. In addition, concrete workabilities had to be ideal for use in slip-form placement into vertical wall forms.

Strength evaluations of alternative concrete mixes began in 1991 and continue to the present. Laboratory trials have focused on the design of a concrete mix that can be readily placed under slip-form wall conditions. To date, the studies have examined concrete mixes with portland cement contents ranging from 420 to 560 pounds per cubic yard of concrete with the addition of fly-ash and microsilica additives. For the cylinders cast and tested, the average 28-day compressive strength is 9,500 psi, with a high of 11,600 psi and a low of 7,850 psi. For the purposes of designing the vacuum containment structure, a compressive strength of 8,000 to 10,000 psi in a workable concrete mix is therefore readily attainable.

The second series of tests involved examining trial batches of concrete mixes to measure permeability. The technique used for these tests measures electrical resistance of the concrete sample. This measurement correlates to the permeability of the concrete and is an AASHTO-approved test for measuring concrete permeability. The compressive strength and workability tests were performed in conjunction with the permeability tests to define specifications for all three parameters. Measurements of less than 750 Coulombs were considered satisfactory because they correlate to a permeability of about 10^{-7} cm/sec. Photographs of the test apparatus with a concrete sample mounted for testing are shown in Figures 6-1 and 6-2.

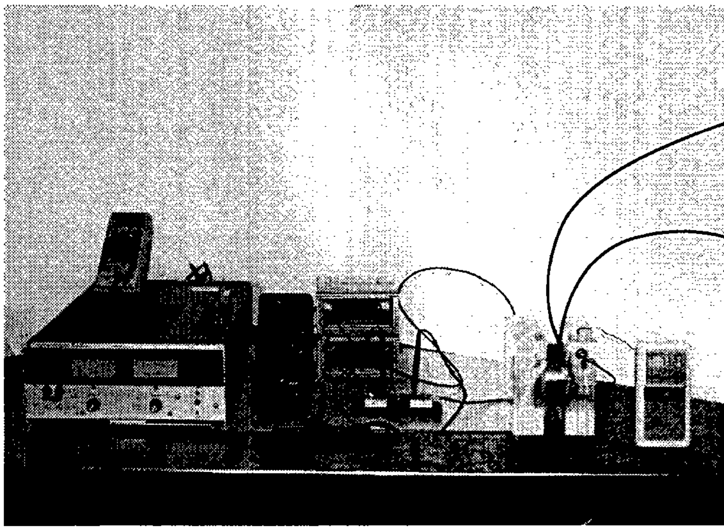


Figure 6-1 - Permeability test apparatus

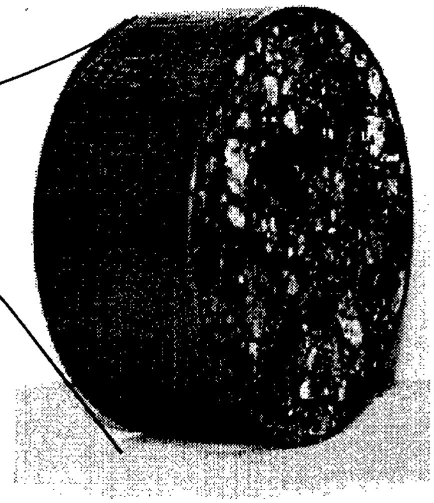


Figure 6-2 - Concrete test sample used in permeability test

The permeability studies used concrete test samples produced by Metropolitan, while the permeability testing was conducted by outside laboratories. Test data collected to date has shown average resistance readings of 260 Coulombs, well below the maximum allowable 750 Coulombs. These results promise excellent permeability performance for the concrete.

Long-Term Durability Issues

The second objective of the concrete tests was to assess the long-term durability of the concrete's surface in an operating environment typical of a distillation process plant. The distillation process creates an operational environment that called into question the durability of a concrete vacuum structure. These concerns include the higher-end temperatures of greater than 200°F, the presence of distilled water (which is very chemically aggressive), and the potential for surface erosion from the water flows in the chamber. These tests combined the high operating temperatures and distilled water environment and assessed the surface erosion potential of the concrete.

Metropolitan constructed the test apparatus shown in Figure 6-3. This apparatus exposed concrete cubes, semi-immersed in a pool of 200°F distilled water, to a distilled water drip over a period of 26 weeks, conditions intended to simulate an operating desalination environment. The cubes were weighed before testing began, and weighed again at regular intervals throughout the test period to determine weight loss from erosion or degradation.

A summary of the long-term durability test results is shown in Figure 6-4. The weekly loss of material increased initially, peaked during the 16th through 18th weeks, and began to decrease to a more or less stable loss rate by the 27th week. Because these tests were conducted on samples mixed from cement and sand (without aggregate), the observed results probably represent a worst-case erosion of the concrete surface. In addition, the material loss rates shown in Figure 6-4 represent losses that occurred due to the direct impact of the distilled water on the surface of the mortar cubes. Visual observations of the portions of the cubes directly immersed in distilled water and not subjected to direct impact dripping, showed no signs of erosion.

Finally, the concrete mixtures used in the distillation tower will include aggregate materials which should further reduce erosion effects. Taken as a whole, these results indicate that any erosion of the concrete's mortar surface will have an insignificant impact on the concrete vacuum vessel during the useful life of the structure.

CONCLUSIONS

- A concrete mix can be readily developed that provides the required compressive strengths ranging from 8,000 to 10,000 psi. This concrete mixture was found to be sufficiently workable for slip-form wall placement.
- The permeability characteristics of the selected concrete mix design are well below the required values of 10^{-7} cm/sec. Consequently, a concrete vessel constructed with this mix should provide an acceptable vacuum and pressure containment barrier.
- The initial losses of concrete surface due to erosion from exposure to a typical operating desalination environment can be accommodated for in the design of the concrete vessel. After an initial material loss, satisfactory longevity and durability of the concrete shell can be expected.

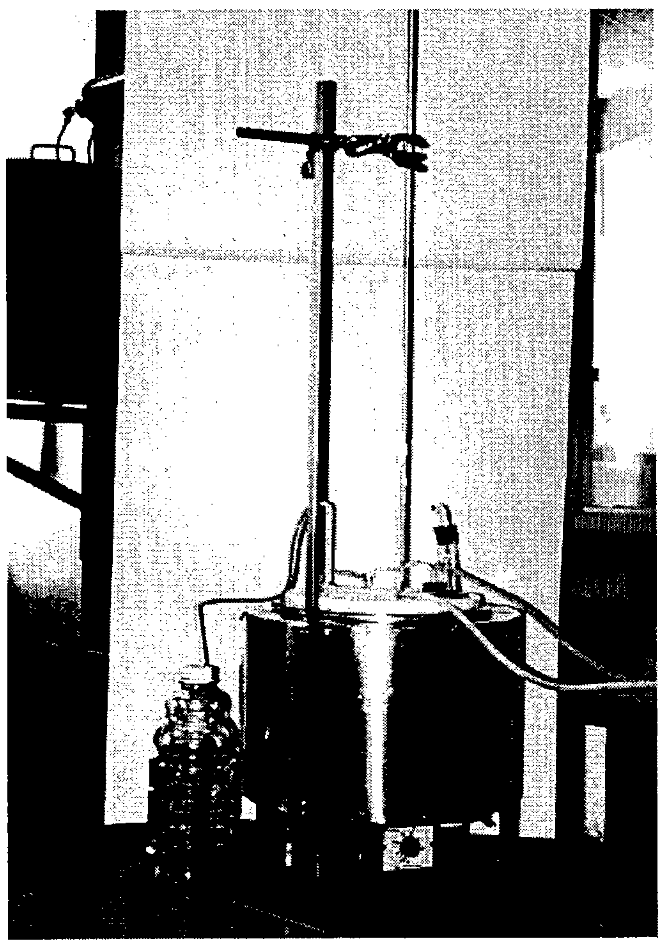


Figure 6-3 - Concrete erosion test apparatus

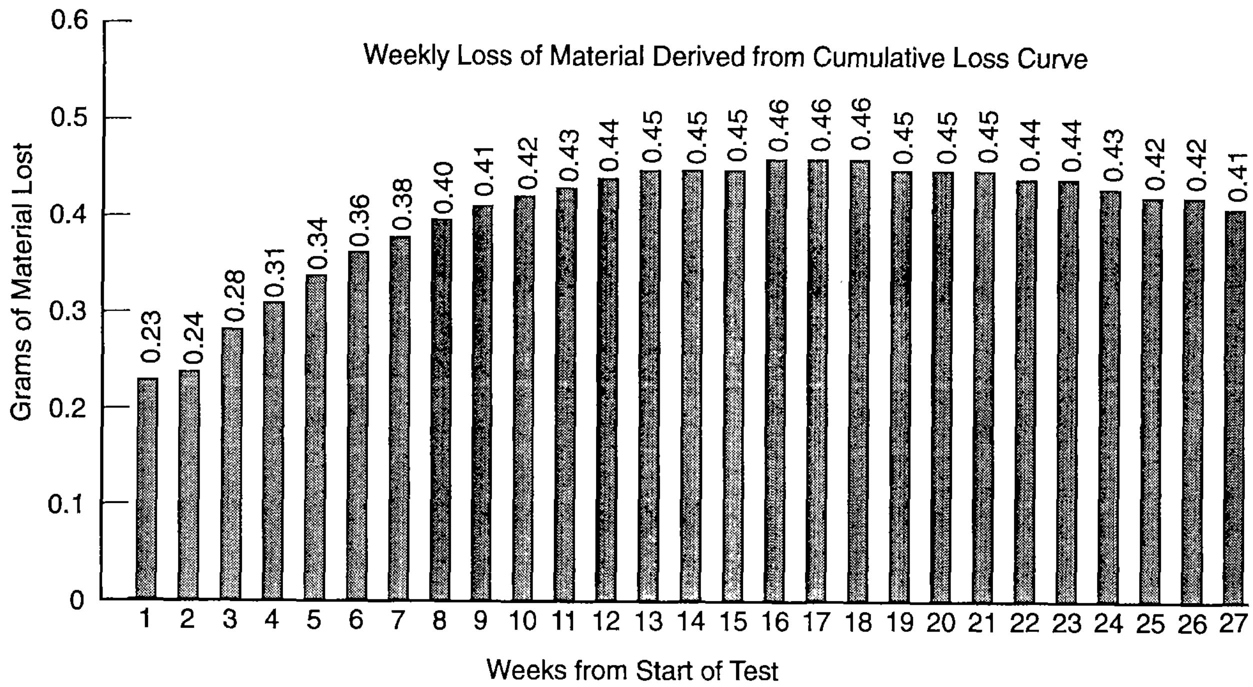


Figure 6-4 - Concrete cube condensation test

CHAPTER 7
INDEPENDENT CONSULTANT'S REVIEW

BACKGROUND

In May 1992, Metropolitan's Board of Directors authorized the engineering consulting firm of Black & Veatch to perform independent technical reviews of the work conducted by Metropolitan staff on this Seawater Desalination Demonstration Program. Thereafter, Black & Veatch conducted several technical reviews of staff work product. As part of its review, Black & Veatch conducted independent tests at the Huntington Beach Test Unit in May 1996 to confirm the performance of the innovative desalination process demonstrated by the short-term test unit (STTU).

CONCLUSIONS

The Black & Veatch work at the Test Unit STTU resulted in the following conclusions.

- The heat transfer rates measured over the operating temperature of 102 to 230°F for the STTU tube bundles exceeded the rates projected in the conceptual design in *Report No. 1084.* Consequently, the heat transfer rates outlined in *Report No. 1084* are conservative values for the Demonstration Plant design.
- The STTU is capable of steady-state operation over the temperature range of 102 to 230°F.
- There is no apparent scaling or fouling of the tubing surfaces, although the test period was not long enough to firmly establish this conclusion.
- The present STTU does not contain sufficient instrumentation to allow a full heat and mass balance to be performed.
- The results of the distillate production tests in the STTU's first effect are scattered. Distillate production from the STTU's second effect could not be obtained because of the plant's present configuration.

RECOMMENDATIONS

The Black & Veatch work at the Test Unit STTU resulted in the following recommendations.

- Additional instrumentation should be installed in the STTU so that complete, precise heat balance calculations around the process unit can be performed in future testing.
- Additional instrumentation should be installed and other modifications performed on the STTU so that distillate production can be quantified precisely in future testing. Black & Veatch has developed a list of STTU modifications required for the heat balance and distillate production tests.

- STTU operation should continue so that long-term heat transfer and tube scaling data can be collected and quantified. This information will establish evaporator tube fouling factors for use in the Demonstration Plant design.
- For future data collection, once a process change is initiated, a process stabilization period should be established. This period should be adhered to since it will allow the process to come to equilibrium before process data is collected, thereby increasing the reliability of the data collected during tests.