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OTEC-1 Power System Test Program: Performance of One-Megawatt Heat Exchangers

J. J. Lorenz, D. Yung, P. A. Howard,
C. B. Panchal, and F. W. Poucher

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OTEC-1 POWER-SYSTEM TEST PROGRAM:
PERFORMANCE OF ONE-MEGAWATT HEAT EXCHANGERS

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J.J. Lorenz, D. Yung, P.A. Howard, C.B. Panchal, and F.W. Poucher

ABSTRACT

Heat exchanger test results for the first deployment of OTEC-1 are reported. These tests were aimed at evaluating the performance of a state-of-the-art, 1-MWe titanium shell-and-tube evaporator and condenser in an ocean environment. The evaporator consisted of both a plain and an enhanced (Union Carbide High Flux) tube bundle, whereas the condenser had plain tubes only. All tests with the evaporator were conducted in the sprayed-bundle mode.

Experimental results for the condenser and plain-tube portion of the evaporator were in excellent agreement with performance predictions. This result demonstrates that the thermal performance of large plain-tube heat exchangers can be predicted with a high level of confidence. However, the performance of the enhanced-tube portion of the evaporator was much lower than predicted. Evidence strongly suggested that this poor performance was attributable mainly to fouling of the High Flux surface by corrosion products consisting predominantly of hydrated aluminum oxides.

1 INTRODUCTION

OTEC-1 is a sea-based, Ocean Thermal Energy Conversion (OTEC) test facility constructed by the U.S. Department of Energy (DOE) for the purposes of evaluating heat exchanger performance, determining the effectiveness of biofouling countermeasures, assessing environmental impacts, and gathering ocean engineering data. A detailed test plan, developed by Argonne National Laboratory (ANL), Lawrence Berkeley Laboratory (LBL), Energy Technology Engineering Center (ETEC), and the National Oceanographic and Atmospheric Administration (NOAA), defined the goals and priorities of the OTEC-1 first deployment test program.¹ This paper focuses on the heat exchanger performance tests that were conducted as part of that program. Other parts of the test program are reported separately.

The major objective of the OTEC-1 heat exchanger test program was to evaluate the performance of a state-of-the-art, 1-MWe titanium shell-and-tube evaporator and condenser in an ocean environment. The evaporator was unique in that it consisted of both a plain and an enhanced (Union Carbide High Flux) tube bundle, whereas the condenser had plain tubes only. Specifically, the OTEC-1 heat exchanger test program included:

- Baseline performance tests to verify design predictions (evaporator and condenser);
- Variable ammonia (NH_3) feed rate tests to determine the optimum reflux ratio (evaporator);
- Activation and deactivation tests to study the nucleation characteristics of the High Flux surface enhancement (evaporator);
- Vapor velocity tests to examine liquid entrainment and carry-over (evaporator);
- Off-normal performance tests to evaluate behavior at different heat duties and water flow rates (condenser);
- Zonal and local measurements to assess performance variations throughout the bundle (evaporator and condenser); and
- Waterside pressure drop measurements to verify design predictions (evaporator and condenser).

All tests with the evaporator were conducted in the sprayed-bundle mode. Originally, a separate series of tests with the evaporator in the flooded-bundle mode was planned, so that thermal performance in both modes (flooded and sprayed) could be compared. However, due to time and budget limitations, tests in the flooded mode were not conducted.

This report presents and discusses the OTEC-1 exchanger test results. Supplemental information on the OTEC-1 heat exchanger test program and experimental hardware can be found in Refs. 1 and 2.

2 OTEC-1 TEST FACILITY

The OTEC-1 test platform (Fig. 1) is a modified Navy T-2 tanker originally named the Chepachet and renamed the Ocean Energy Converter. Only modest structural changes were required to adapt the vessel for the OTEC-1 test program. Existing power, piping, accommodations, and other features were modified to satisfy all requirements for testing the 1-MWe heat exchangers.

The OTEC-1 test evaporator, condenser, and the balance of the test loop are installed in an enclosed compartment (called the OTEC compartment) in the forward portion of the ship. Figure 2 shows the evaporator being lowered into the OTEC compartment, which was created by removing bulkheads between the centerline cargo tanks. All operating ammonia systems are confined to this compartment within a watertight boundary below the main deck. Ammonia storage tanks and auxiliary systems equipment are on the forward main deck above the OTEC-1 compartment.

The two test heat exchangers are positioned parallel to the ship's centerline at elevations within a few yards of the operating waterline to minimize the effects of ship motion.

Controls and instrumentation for the OTEC-1 system are located in a self-contained, air-conditioned van. The van is on a platform aft of the midship deckhouse for convenient access to OTEC-1 operating crew accommodations and the OTEC compartment.

The OTEC-1 facility has a warm and a cold seawater supply system. The cold water system consists of the cold water pipe, a sump (moon pool), a variable speed pump, the condenser, and the water discharge system. Cold

Fig. 1 OTEC-1 Test Platform

Fig. 2 Evaporator Being Lowered into the OTEC Compartment

seawater is drawn in through a screen at the bottom of a 2000-ft long cold water pipe. The pipe is made up of three 48-in. diameter polyethylene pipe sections with upper and lower steel transition elements. At the upper end, the pipes merge into a single flow and attachment channel. Seawater flows upward through the cold water pipe and to the sump. From there the water is pumped through the condenser into a port wing tank where it mixes with the water effluent from the evaporator.

The warm water system consists of water intakes, a sump, a pump, the evaporator, a discharge system, and associated piping. Warm seawater is drawn through a screened opening in the hull and into the warm water sump. From there the water is pumped through the evaporator to a port wing tank, where it mixes with the condenser effluent. The mixed effluent is pumped through the discharge system into the ocean.

3 1-MWe HEAT EXCHANGER TEST DESCRIPTION

3.1 TEST ARTICLES

Both the evaporator and condenser are shell-and-tube heat exchangers with seawater on the tube side and ammonia on the shell side. Geometrical features and design characteristics are shown in Figs. 3 and 4; ammonia-loop interfaces are shown in Fig. 5.

The evaporator (Fig. 3) is actually two units in one: a plain-tube upper bundle and an enhanced-tube (High Flux) lower bundle. The performance characteristics of each bundle can be measured separately. The evaporator is designed to operate in either a sprayed or flooded mode. In the flooded mode, the shell of the evaporator is filled with liquid ammonia, such that all or part of the tube bundle is submerged in a pool of ammonia. Nucleate boiling is the primary mechanism of heat transfer on the outside of the tubes.

Fig. 3 Evaporator Design

Fig. 4 Condenser Design

In the sprayed mode of operation, ammonia liquid is directed onto the tubes from nozzles situated at the top plane and mid plane of the evaporator. The top-plane feed system consists of two separate sets of nozzles (a low-pressure, high-flow set and a high-pressure, low-flow set) and the mid plane consists of a single set (high-pressure, low-flow). Thin-film evaporation is the primary mechanism of heat transfer on the outside of the plain tubes and nucleate boiling is the primary mechanism on the enhanced tubes. A side shroud plate, shown in Fig. 3, was installed to limit vapor flow to one direction only, simulating the crossflow characteristics of a 4-MWe evaporator. All tests were performed with this simulated 4-MWe configuration.

The condenser (Fig. 4) has plain tubes only. Ammonia vapor (slightly superheated) enters at the top and condenses in a filmwise manner on the tube surfaces. The condensate falls to the bottom of the shell and is collected in five drain lines, each of which has a turbine flowmeter for measuring the condensate flow rate. Noncondensable gases are removed via four vents located near the bottom of the bundle.

Fig. 5 OTEC-1 Power Loop Interfaces

In both heat exchangers, ammonia temperatures and pressures are measured on the shell side, and seawater temperatures and pressures are measured in the inlet and outlet waterboxes. The outlet waterbox of each heat exchanger is instrumented with a rake of Resistance Temperature Detectors (RTDs) for evaluating zonal performance over the bundle cross section. Each heat exchanger is also equipped with instrumented loops for measuring the performance of individual tubes within the bundle.

Biofouling in the heat exchangers is controlled by intermittent chlorination (0.4 ppm for one hour each day) in combination with continuous Amertap (one ball every 15 minutes for each tube). Two ANL biofouling and corrosion modules are used to track the buildup of fouling in the evaporator and condenser (one module for each unit). During the first deployment, measurements with the modules yielded no evidence of heat exchanger tube-side fouling. The lack of tube-side fouling was further inferred from the fact that the overall heat exchanger performance did not degrade with time.

3.2 INSTRUMENTATION

The target accuracy for measuring the overall heat transfer coefficient (U_o) was $\pm 10\%$. To achieve this, temperatures had to be measured to within $\pm 0.125^\circ\text{F}$ and seawater flow rates to within $\pm 5\%$ (of reading). Generally, these accuracy goals were met or surpassed. A special copper-block technique was used for end-to-end calibration of the RTDs.

Before testing began, most of the critical power loop instrumentation was fully checked out and calibrated in accordance with the OTEC-1 test plan requirements. During the test program, the bulk of the OTEC-1 instrumentation functioned satisfactorily, enabling acquisition of most of the originally planned test data. However, a number of instrumentation failures resulted in losses of data. These failures included: (1) the turbine

flowmeters and RTDs in the condenser drain lines, resulting in a loss of data on the axial condensate flow profile; (2) the sonic flowmeter in the demister return line, resulting in a loss of data on liquid carry-over; (3) the instrumented loop flowmeters and RTDs in both the evaporator and condenser, resulting in a loss of data on individual tube performance; (4) pressure transducers in the condenser inlet and outlet waterboxes, resulting in a loss of the pressure-drop data for comparison with design predictions; and (5) the sonic flowmeters in both the warm and cold seawater systems, resulting in a loss of data needed for heat balance checks.

In the case of the seawater sonic flowmeters, it was discovered that the transmission signals were being attenuated by bubbles in both the warm and cold seawater systems. Corrective actions were taken in an attempt to eliminate the bubbles. As a result, the population of bubbles was reduced dramatically, but not enough to mitigate the attenuation problem. Later, two other sonic flowmeters were tried: a transmission type having a higher signal strength and a Doppler type. Results with these meters, although encouraging, were judged to be unsatisfactory. After exploring a number of alternative means for measuring flow, it was decided simply to calculate the warm and cold seawater flow rates from heat duty measurements on the ammonia side -- i.e., by equating the ammonia-side heat duty (measured) to the waterside heat duty (unknown) and solving for the seawater flow rate. This technique is expected to yield a flow rate accuracy of $\pm 5\%$, but can be employed only when the ammonia system is operational and heat is being transferred. The main disadvantage of not having a direct seawater flow rate measurement is that no independent waterside/ammonia-side heat balance checks can be made.

3.3 DATA ACQUISITION AND REDUCTION

The OTEC-1 test facility has a minicomputer-based data acquisition system (DAS) that can sample and record all channels of data, apply calibration and correction factors to these data, and provide real-time computation and display (with hard copy) of selected calculated quantities and sensor readings in engineering units. Data can be recorded on disk and tape at independently selected rates. During first deployment testing, data were generally recorded on tape at a rate of one sample per minute. Original data tapes were analyzed on board in real time and duplicate tapes were sent to ANL for more detailed evaluation of the test results.

The data reduction program is based largely on the equations developed in the OTEC-1 test plan.¹ Only a few minor changes had to be made to the original program. For example, heat duty is now calculated solely on the basis of ammonia-side measurements. Also, in the prediction of U_o for the lower (enhanced) portion of the evaporator, account is now taken of the fact that only 90% of the active tube length consists of the High Flux enhancement.

3.4 OPERATING PROCEDURE

The normal start-up procedure for the ammonia system is as follows (seawater system already running):

1. Purge power loop with nitrogen until residual air-to-ammonia ratio is diluted well below explosive limit;
2. Transfer ammonia into evaporator sump;
3. Close throttle valve (V-111) located in vapor line between evaporator and condenser;
4. Start ammonia reflux pump to initiate ammonia spray;
5. As vapor is generated and evaporator pressure begins to rise, open V-111 to allow vapor to flow to condenser;
6. When level of condensate rises in central condenser drain line, start condensate return pump;
7. Monitor ammonia levels in the condensate drain line and evaporator sump; and
8. Adjust valve V-111 as required to achieve desired heat duty and allow system to stabilize.

The evaporator pressure, and hence heat duty, is controlled by the setting of valve V-111. The ammonia loop control system is capable of maintaining either constant heat duty or constant pressure in the evaporator. Generally, either mode of control is acceptable. However, for the reflux ratio tests, it was convenient to hold the evaporator pressure constant and allow the heat duty to vary.

Following system start-up, steady-state conditions were generally attained in about two hours unless the sea state was unusually high. During rough weather, it was difficult to maintain steady operation of the ammonia system, mainly because of sloshing of ammonia in the sumps. Also, cavitation of the ammonia reflux pump occurred when the ammonia level in the evaporator sump (drain tank) was low.

When a change was made from an established test condition to a new (slightly different) test condition, steady operation at the new condition was usually reached in less than 30 minutes. All tests were conducted for a minimum of 30 minutes. Typically, the duration of a given test ranged from 30 minutes to 2 hours. In a special test to study long-term activation of the enhanced surface, the duration was extended to 35 hours.

4 TEST RESULTS

A total of 95 tests were conducted during 370 hours of ammonia system operation over a three-month period, January through March 1981. Operating ranges are shown in Table 1 and a tabulation of individual runs is given in Appendix A. Tests 1-29 were regarded as shakedown runs for debugging the system and gaining operational experience. During these initial shakedown tests, the water content of the ammonia was unacceptably high ($\approx 0.9\%$ by weight); by distillation, the water content was reduced to a tolerable level ($< 0.4\%$ by weight) before Tests 30-95 were conducted.

4.1 EVAPORATOR TESTS

4.1.1 Adiabatic Conditions

To establish confidence in the seawater temperature measurements, the inlet and outlet average waterbox temperatures were compared under adiabatic conditions (i.e., with the ammonia system shut down), as shown in Fig. 6. These temperatures were in excellent agreement. Also, the individual exit RTD readings agreed within the calibration tolerance of $\pm 0.125^\circ\text{F}$, except for two RTDs near the center, which read 77.09°F and 77.59°F (see Fig. 6).

4.1.2 Baseline Thermal Performance

Baseline test results are presented in Table 2. The measured value of U_o for the plain-tube portion of the evaporator is in perfect agreement with the prediction. Although this perfect agreement is somewhat fortuitous (because the absolute accuracy of the measured U_o is only $\pm 10\%$), it shows that the thermal performance of the plain-tube, sprayed-bundle evaporator can be predicted with a high level of confidence. The predicted U_o value for the plain-tube bundle was based on a waterside coefficient of $1330 \text{ Btu/hr}\cdot\text{ft}^2\cdot^\circ\text{F}$ from the Petukhov-Popov correlation³ and an ammonia-side coefficient of $1000 \text{ Btu/hr}\cdot\text{ft}^2\cdot^\circ\text{F}$ from Conti's single-tube data.⁴ Zero fouling was assumed.

Table 1 Heat Exchanger Operating Ranges

Parameter	Evaporator	Condenser
Heat duty (MWt)	14-46	14-46
Seawater flow (gpm)	57,000-91,000	32,000-67,000
Seawater temperature ($^\circ\text{F}$)	76-78	41-43
Ammonia feed rate ^a (gpm)	400-3700	NA
Ammonia shell-side parameters		
Pressure (psia)	128.8-133.4	82.7-99.7
Saturation temperature ($^\circ\text{F}$)	70-72	46-56

^aTotal combined feed rate from all nozzles.

NA = not applicable.

EVAPORATOR OUTLET WATERBOX

Fig. 6 Seawater Temperatures in Evaporator Outlet Waterbox: Adiabatic Conditions

Table 2 Baseline Test Results for U_o and Δp^a

Heat Exchanger	U_o (Btu/hr·ft ² ·°F)		Δp (psi)	
	Measured ^b	Predicted	Measured ^b	Predicted
Evaporator				
Plain bundle	490	490	2.7	2.5
Enhanced bundle	600 ^c	735	2.7	2.5
Condenser	480	490	d	2.9

^a U_o = overall heat transfer coefficient; Δp = waterside pressure drop through heat exchanger; nominal conditions were: heat duty = 40 MWt; ammonia feed rate = 3300 gpm; warm water flow rate = 83,000 gpm; cold water feed rate = 67,000 gpm.

^bMeasurement accuracy: $\pm 10\%$ for U_o ; $\pm 2\%$ for Δp .

^cPartially activated (see Fig. 6).

^dPressure transducer out of calibration.

Table 2 shows that the measured performance of the enhanced-tube portion of the evaporator is considerably lower than predicted. This poor performance is thought to be caused mainly by fouling of the High Flux surface by corrosion products, as will be discussed further in Sec. 4.1.4. The predicted U_o value for the enhanced bundle was based on the same waterside coefficient as was used for the plain-tube bundle, and on an ammonia-side coefficient of 3800 Btu/hr·ft²·°F from ANL experiments with a small-scale Union Carbide sprayed bundle.⁵ (Originally, ANL reported an ammonia-side coefficient of 4600 Btu/hr·ft²·°F, but later revised that value to 3800 Btu/hr·ft²·°F based on an improved Wilson plot procedure.) The predictions accounted for the fact that 10% of the active tube length did not have High Flux.

4.1.3 Reflux Ratio

The power consumed by the ammonia reflux pump represents a parasitic loss in the system; therefore, it is important to optimize (minimize) the feed rate. Figure 7 gives the results for the plain bundle. As the feed rate is reduced, U_o remains constant until a critical (minimum) feed rate of 1000 gpm is reached. Below this critical feed rate, U_o drops sharply as film breakdown and dryout occur on the lowermost tubes in the bundle. At this critical condition, the critical local flow rate on the lowermost tubes is about 45 lbm/hr·ft. This critical flow rate is an important design parameter because it defines the operating limit of any plain-tube spray evaporator for

Fig. 7 Influence of Feed Rate on Evaporator Performance: Plain-Tube Bundle

OTEC application: it represents the minimum flow that must be supplied to the lowermost tubes to ensure complete wetting and, hence, optimum performance of the evaporator. As expected, this minimum flow rate of 45 lbm/hr·ft for plain tubes is higher than the value of 20 lbm/hr·ft obtained in tests at ANL with High Flux enhanced tubes because the plain tubes are not as easily wetted and the film breaks down sooner.

Figure 7 shows that evaporator performance is not strongly affected by the spray system used, whether it be top low-pressure nozzles only, top high-pressure only, or a combination of the two.

Results for the enhanced bundle are presented in Fig. 8. The term "effective ammonia feed" refers to the net amount of ammonia liquid reaching the lower bundle. Depending on the method of system start-up (see Sec. 4.1.4), the data fell on either the upper or lower "curve." The lower curve (deactivated) is similar to the performance of the smooth tube in Fig. 7. Actually, the enhanced-tube performance of 430 Btu/hr·ft²·°F is somewhat poorer than the plain-tube performance of 490 Btu/hr·ft²·°F because the deactivated High Flux surface acts as a sponge and holds a stagnant insulating layer of ammonia liquid. An ammonia layer of about 1 mil would account for the difference.

Fig. 8 Influence of Feed Rate on Evaporator Performance:
Enhanced-Tube Bundle

When the enhanced surface was partially activated (by changing the method of start-up), the performance improved, but remained well below the predicted level. Based on a measured value of U_o equal to 600 Btu/hr·ft²·°F, the ammonia-side coefficient was calculated to be 1720 Btu/hr·ft²·°F, which is only 45% of the predicted value of 3800 Btu/hr·ft²·°F. Reasons for the poor performance of the enhanced surface are discussed in the next section.

An interesting hysteresis effect was observed when the surface was partially activated. The upper curve in Fig. 8 could not be retraced after the feed rate was reduced below about 500 gpm and then increased. Instead, the data fell on the lower curve when the feed rate was increased, indicating that the surface had become deactivated during operation at the lower feed rates.

4.1.4 Performance of the High Flux Surface

Unless special start-up and operating procedures were employed, the enhanced tubes invariably behaved as plain tubes (i.e., the lower curve in Fig. 8). Three different procedures to activate the nucleation sites were tried: (1) initially drying out the tubes by shutting off the ammonia feed and opening the throttle valve between the evaporator and condenser for a specified length of time; (2) increasing the excess superheat for nucleation by temporarily reducing the evaporator pressure while maintaining the ammonia feed; and (3) pulling a partial vacuum (15 inHg) for an extended period to evaporate volatile liquid (e.g., water) occluded in the pores (unfortunately, a sufficiently large vacuum pump was not available to pull a harder vacuum). Of these three procedures, the dryout operation proved to be the most successful, but it still only partially improved the heat transfer performance of the enhanced surfaces, which remained well below the predicted level, even on a local basis. See Sec. 4.1.5 for a discussion of local variations of U_o throughout the bundle.

Evidence strongly suggested that the poor performance of the enhanced bundle was attributable mainly to fouling of the High Flux surface. Union Carbide Corp. examined a section of High Flux tubing removed from the OTEC-1 evaporator and found that the tube was fouled with a layer of white crystalline material identified by X-ray diffraction analysis as bayerite or hydrated beta aluminum hydroxide $Al(OH)_3$, with a small amount of iron oxide.⁷ These corrosion deposits were embedded in the porous surface and, hence, destroyed the nucleation sites. Union Carbide is trying to identify an effective cleaning method for rejuvenating the surface.

Union Carbide tested a section of the fouled tubing in the as-received condition and compared it with an original control tube (from the 1979 production run), which was retested at the same time.⁷ Water was passed through the inside of the tube and freon-11 was boiled on the outside. Because the tests were conducted with freon instead of ammonia, the relative behavior was more important than absolute coefficients. The test results indicated a substantial degradation of performance of the fouled tube relative to the original (clean) tube. The ratio of boiling coefficients (fouled/clean) was 0.38, which compares favorably with the ratio of 0.45 deduced from the OTEC-1 test data (see Sec. 4.1.3). These results support the hypothesis that the poor performance observed on board OTEC-1 was due mainly to fouling.

Union Carbide's metallurgy department suspects that the corrosion of the High Flux enhancement was produced by prolonged exposure of the tubes to a warm, humid marine atmosphere. An alternate possibility is a chemical reaction between aluminum and ammonia in the presence of small amounts of seawater. A complete analysis of the problem must take into account the entire history of conditions to which the heat exchanger was exposed throughout its lifetime -- from initial fabrication through final deployment and testing. In any case, one thing is certain: fouling of the High Flux surface must have occurred prior to the start-up of ammonia system operation because the poor performance was detected at the very outset of testing -- there was no further degradation with time.

In addition to fouling, there were less-important factors that could have contributed to the poor performance of the High Flux tubes. A post-test inspection revealed widespread plugging of the mid-plane spray nozzles. This should not, however, have had a major effect on heat exchanger performance for two reasons: (1) the mid-plane nozzles provided only make-up feed to the lower bundle, and (2) the top-plane nozzles, which provided the primary feed to both bundles, must have been functioning properly, as evidenced by the excellent performance of the upper bundle. The post-test inspection also revealed oily patches on portions of the tube surfaces. Moreover, oil was present on the tube sheets, tube support baffles, and inside walls of the evaporator shell. Presumably, this was ammonia pump lubricating oil that leaked past the pump seal and into the ammonia system.

4.1.5 Bundle-Depth and Vapor Velocity Effects

Figure 9 shows the zonal distribution of U_o in the exit waterbox of the evaporator for a run in which the lower (enhanced) half was deactivated. The U_o values are fairly uniform within each half of the evaporator. The uniformity in the vertical direction indicates that liquid-loading effects are small; the uniformity in the horizontal direction reveals that vapor velocity effects are insignificant. The unimportance of vapor velocity also was observed during earlier shakedown runs in which U_o was generally found to be unaffected when the heat duty, and hence vapor velocity, was reduced to 60% of nominal. This result was expected on the basis of ANL's analysis⁶ showing that a crossflow velocity of at least 5 ft/sec is required to deflect the falling film. The maximum crossflow in the evaporator was only 3 ft/sec in the gaps between the outermost tubes. Although the vapor velocity was too low to cause gross entrainment and liquid redistribution within the bundle, there may have been some carry-over of small droplets produced by fracture and splashing as the ammonia liquid spray impinged on the uppermost tubes. Unfortunately, a failure of the sonic flowmeter in the phase-separator (demister) return line precluded a quantitative assessment of liquid carry-over.

Figure 10 shows the zonal distribution of U_o for a case where the lower bundle is partially activated. As in Fig. 9, the distribution of U_o in the upper bundle is fairly uniform. However, the U_o values in the lower bundle range from a high value of 651 Btu/hr·ft²·°F in the center to a low of 521 Btu/hr·ft²·°F in the upper left hand corner. This variation is considered to be caused not by vapor velocity or bundle-depth effects, but by differences in the nucleation characteristics of the tubes resulting from varying degrees of fouling throughout the bundle.

UNITS = Btu/hr. ft².°F

EVAPORATOR OUTLET WATERBOX

Fig. 9 Distribution of U_o in Evaporator Outlet Waterbox with Lower Bundle Deactivated

It was originally intended to study vapor velocity effects by conducting a separate series of tests with the side shroud removed (1-MWe configuration) and making a comparison with results obtained with the side shroud in place (4-MWe configuration). The vapor velocity in the 1-MWe configuration would be half that in the 4-MWe configuration. However, since tests with the latter configuration clearly showed an absence of vapor velocity effects, separate tests with the 1-MWe configuration -- which has an even lower vapor velocity -- were deemed unnecessary.

4.1.6 Local Shell-Side Temperatures

The evaporator shell-side temperature distribution was found to be uniform both axially and circumferentially (see Fig. 11). The measured shell-side temperatures were in excellent agreement with the saturation temperature calculated at the shell-side pressure. Among other things, the existence of a saturated vapor state indicates that the ammonia is pure. In the early shakedown tests with water in the ammonia, the state of the vapor was not saturated, but superheated.

EVAPORATOR OUTLET WATERBOX

Fig. 10 Distribution of U_o in Evaporator Outlet Waterbox with Lower Bundle Partially Activated

4.1.7 Waterside Pressure Drop

The measured pressure drop between the inlet and outlet waterbox agreed favorably with predictions, as shown in Table 2.

4.1.8 Effect of Vapor Bypass to Evaporator Sump

During operation, it was found that the temperature of the ammonia feed was nearly equal to the saturation temperature in the evaporator, suggesting that some ammonia vapor from the evaporator must have been flowing downward through the drain line and condensing directly into the evaporator sump (drain tank). An energy balance on the sump revealed that this bypass flow amounted to about 5% of the total vapor generated within the evaporator. The original data reduction program did not account for the bypass flow and calculated the evaporator heat duty solely on the basis of the vapor exiting at the top of the evaporator (as measured by a Venturi flowmeter in the vapor line). Thus, the evaporator heat duty calculation was 5% low. Also, the U_o value and the seawater flow rate were 5% low since they were both calculated from the heat duty. The results given in this report are based on the original data reduction program and hence do not reflect the 5% correction. Nevertheless, the primary conclusions drawn from the data remain the same.

Fig. 11 Local Evaporator Shell-Side Temperatures

Vapor bypass is undesirable and probably can be prevented by reducing the diameter of the evaporator drain lines.

4.1.9 Effect of Ship Motion

There was no apparent influence of ship motion on evaporator performance: data taken during high sea states were similar to data taken during calm weather. However, maintaining steady operation of the ammonia system was difficult during high sea states. Also, cavitation of the reflux pump was experienced when the ammonia level was low.

4.2 CONDENSER TESTS

4.2.1 Adiabatic Conditions

As in the case of the evaporator, the condenser inlet and outlet average waterbox temperatures were in excellent agreement, and the individual outlet waterbox RTDs agreed to within the calibration tolerance of $\pm 0.125^\circ\text{F}$ (see Fig. 12).

4.2.2 Baseline Thermal Performance

Baseline results for the condenser are given in Table 2. Typically, ammonia vapor entered the condenser superheated by about 6°F and ammonia condensate left the condenser subcooled by about 1°F. Here, as in the case of the plain-tube evaporator, the thermal performance is predictable to a high level of accuracy. The predicted U_o value was calculated on the basis of a waterside coefficient of 980 Btu/hr·ft²·°F from the Petukhov-Popov correlation and an ammonia-side coefficient of 1428 Btu/hr·ft²·°F in accordance with the original thermal design calculations of C.F. Braun and Co.

CONDENSER OUTLET WATERBOX

4.2.3 Performance at Off-Normal Conditions

Figure 13 shows condenser thermal performance over a range of heat duties (from 18 MWt to 47 MWt) and flow rates from 32,000 gpm to 67,000 gpm). Over the entire parametric range, predictions are in excellent agreement with the measured U_o values. The data exhibit a negligibly small dependence on heat flux, suggesting that the condenser was free of noncondensables. In tests conducted prior to purging, the U_o value of the condenser was observed to drop markedly at low heat duties.

Fig. 12 Seawater Temperature in Condenser Outlet Waterbox: Adiabatic Conditions

4.2.4 Bundle-Depth Effects

The distribution of U_o in the exit waterbox is presented in Fig. 14. As expected, the zonal U_o values are fairly uniform in a given horizontal plane, but decrease with bundle depth as a result of condensate inundation.

4.2.5 Effect of Noncondensable Gases

Figure 15 shows the distribution of U_o in the exit waterbox before purging. Comparison of Figs. 14 and 15 shows that noncondensable gases tend to build up in the lower half of the condenser. Generally, it was found that several three-minute purges were adequate to remove noncondensable gases.

Fig. 13 Condenser Performance over a Range of Heat Duties and Water Flow Rates

4.2.6 Waterside Pressure Drop

Due to a faulty (out-of-calibration) waterbox pressure transducer, no valid measurements were obtained for comparison with predictions (see Table 2).

4.2.7 Effect of Ship Motion

As in the case of the evaporator, ship motion had no discernible effect on performance, but caused some unsteadiness in the operation of the ammonia system.

CONDENSER OUTLET WATERBOX

Fig. 14 Distribution of U_o in Condenser Outlet Waterbox after Purge

CONDENSER OUTLET WATERBOX

Fig. 15 Distribution of U_o in Condenser Outlet Waterbox before Purge

5 CONCLUDING REMARKS

During the first deployment of OTEC-1, most of the instrumentation and power loop components functioned satisfactorily, enabling the bulk of the originally planned test data to be acquired. There were, however, a number of instrumentation problems that resulted in a loss of certain data. Nevertheless, most of the essential OTEC-1 test objectives were satisfied.

Experimental results for the condenser and plain-tube portion of the evaporator were found to be in excellent agreement with performance predictions. This result demonstrates that the thermal performance of large plain-tube heat exchangers can be predicted with a high level of confidence. On the other hand, the performance of the enhanced-tube portion of the evaporator was much lower than predicted. Evidence strongly suggested that this poor performance was attributable mainly to fouling of the High Flux surface by corrosion products consisting predominantly of hydrated aluminum oxides.

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APPENDIX A
TABULATION OF INDIVIDUAL TEST RUNS

Appendix A: Tabulation of Individual Test Runs

Test	Description	Heat Duty (MWt)	Warm Water Flow Rate (gpm)	Ammonia Feed Rate (gpm)		Mid- Plane	U _o (Btu/hr·ft ² ·°F)		Flow Rate (gpm)	U _o (Btu/hr·ft ² ·°F)
				Top Nozzles			Plain (upper)	Enhanced (lower)		
				Low-Pressure	High-Pressure					
1-29	Shakedown tests									
30	Distillation & evacuation	0	78,000	0	0	0	N/A	N/A	55,000	N/A
31	Surface conditioning	0	78,000	0 for dry 1500 for wet	0	0	N/A	N/A	55,000	N/A
32	Baseline	39	78,000	1500	0	0	460	410	55,000	450
33	Surface conditioning	0	82,000	0	0	0	N/A	N/A	55,000	N/A
34	Baseline	37	82,000	2200	0	0	485	565	55,000	455
35	Deluge	35	82,000	2200	0	0	480	560	55,000	455
36	Reflux ratio tests ↓	35	82,000	1500	0	0	475	535	55,000	450
37		35	82,000	1200	0	0	480	505	55,000	455
38			82,000	950	0	0	475	410	55,000	455
39		32	82,000	800	0	0	460	310	55,000	455
40		28	82,000	660	0	0	430	165	55,000	450
41		24	82,000	550	0	0	390	80	55,000	450
42	Baseline	35	82,000	2200	0	0	485	420	55,000	450
43	Reflux test	31	82,000	950	0	0	a	a	55,000	445
44	Surface conditioning	0	82,000	1500 for wet 0 for dry	0	0	N/A	N/A	55,000	N/A
45	Reflux ratio tests ↓	46	85,000	3000	0	0	490	450	55,000	445
45		45	85,000	1500	0	0	490	395	55,000	450
47		39	85,000	950	0	0	470	250	55,000	455
48		29	85,000	660	0	0	400	75	55,000	455
49		45	85,000	2200	0	0	490	435	55,000	450

Appendix A: Tabulation of Individual Test Runs (Cont'd)

Test	Description	Heat Duty (MWt)	Warm Water Flow Rate (gpm)	Ammonia Feed Rate (gpm)		Mid- Plane	U _o (Btu/hr·ft ² ·°F)		Flow Rate (gpm)	U _o (Btu/hr·ft ² ·°F)
				Top Nozzles			Plain (upper)	Enhanced (lower)		
				Low-Pressure	High-Pressure					
50	Reflux ratio	18	83,000	0	0	930	N/A	500	55,000	420
51	tests: mid-	19	83,000	0	0	795	N/A	450	55,000	420
52	plane feed	17	83,000	0	0	600	N/A	385	55,000	415
53	only	14	83,000	0	0	400	N/A	240	55,000	400
54	Reflux ratio	30	83,000	0	960	0	415	285	55,000	435
55	tests: top	28	83,000	0	795	0	400	175	55,000	435
56	high pressure	23	83,000	0	600	0	365	60	55,000	435
57	nozzles only	16	83,000	0	400	0	270	Dryout	55,000	420
58	Reflux ratio	32	83,000	2730	965	0	475	430	55,000	440
59	tests: nozzle	32	83,000	2370	970	0	480	425	55,000	445
60	combinations	32	83,000	2045	975	0	475	430	55,000	445
61	↓	33	83,000	1520	975	0	470	420	55,000	440
62		34	83,000	2525	0	0	480	430	55,000	440
63		28	83,000	1285	885	0	480	425	55,000	440
64		34	83,000	1355	900	0	480	425	55,000	440
65		41	83,000	1410	930	0	475	415	55,000	450
66		41	83,000	1000	520	0	485	365	55,000	445
67		33	83,000	950	500	0	485	380	55,000	450
68	Repeatability	25	83,000	910	0	475	485	420	55,000	435
69	Surface conditioning	0	83,000	0	0	0	N/A	N/A	55,000	N/A
70	Repeatability	34	83,000	2515	0	0	490	N/A	55,000	445
71	Condenser	32	83,000	2490	0	0	490	550	55,000	445
72	tests	31	83,000	2505	0	0	485	550	32,000	340
73	↓	31	83,000	2510	0	0	485	545	66,000	485
74		45	83,000	2495	0	0	485	540	68,000	490
75		45	83,000	2490	0	0	480	540	58,000	455
76		44	83,000	2495	0	0	470	530	a	a
77		17	83,000	0	610	380	425	410	32,000	325
78		19	83,000	0	705	475	425	420	57,000	440
79		19	83,000	0	795	580	425	420	67,000	470

Appendix A: Tabulation of Individual Test Runs (Cont'd)

Test	Description	Heat Duty (MWt)	Warm Water Flow Rate (gpm)	Ammonia Feed Rate (gpm)		Mid- Plane	U _o (Btu/hr·ft ² ·°F)		Flow Rate (gpm)	U _o (Btu/hr·ft ² ·°F)
				Top Nozzles			Plain (upper)	Enhanced (lower)		
				Low-Pressure	High-Pressure					
80	Repeatability	28	91,000	0	600	365	410	375	57,000	455
81	↓	24	76,000	0	595	450	395	430	44,000	400
82	Activation	41	83,000	1005	0	0	460	235	44,000	395
83	tests	21	83,000	1000	0	0	500	425	44,000	385
84	↓	22	83,000	1000	0	0	495	495	44,000	395
85		41	83,000	1000	0	0	480	295	44,000	405
86	Miscellaneous	38	83,000	800	0	0	590	Dryout	44,000	410
87	repeatability	38	83,000	0	805	0	495	Dryout	44,000	405
88	and reflux	22	91,000	0	490	0	232	Dryout	29,000	320
89	ratio tests	17	57,000	1190	0	0	430	370	67,000	470
90		32	83,000	2560	0	920	485	605	44,000	405
91	↓	32	83,000	3025	0	0	485	595	44,000	410
92		32	83,000	1490	0	0	485	565	44,000	410
93		32	83,000	950	0	650	480	555	44,000	410
94	↓	29	83,000	0	800	810	415	530	44,000	410
95		13	79,000	0	810	810	445	490	44,000	380

^aInsufficient time to reach steady state.

N/A = Not applicable.

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