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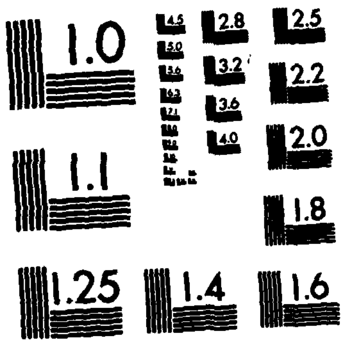

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WATERBORNE NOISE DUE TO OCEAN THERMAL ENERGY CONVERSION PLANTS

C. P. Janota and D. E. Thompson

Technical Memorandum
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The contents of this memorandum are to be submitted for publication in the Journal of the Acoustical Society of Anerica.

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Table of Contents

List of Tables

List of Figures

List of Figures (Cont'd)

List of Symbols and Abbreviations With Units

a	radius of a cylinder or rotor, m
b	characteristic transverse dimension of a body, m
C_0	speed of sound in sea water, use 1500m/sec
C_1	speed of sound in material of interest, m/sec
C_f'	local boundary-layer wall shear stress
d	characteristic dimension for computation, m
f	frequency, Hz
h	thickness of a plate or wall, m
hp	metric horsepower, 75 kgm/sec or 735.49W
k	acoustic wave number
ℓ	correlation length, m
M	Mach number, $M= U_1/C_0$
MWe	megawatts net electrical power
MWt	megawatts gross thermal power
R	Reynolds number, in water $R = U_0 d/1.3x10^{-6}$ at 10°C
R_{crit}	critical Reynolds number
r_h	hub radius of a rotor, m
rps	revolutions per sec, sec^{-1}
S	cross-sectional or surface area, m^2
S_N	Strouhal number
T	turbulence parameter, $T = U_t/U_0$
U	rotor tip speed, m/sec

U_0	mean velocity of flow, m/sec
U_1	component of flow, m/sec
U_t	mean turbulence velocity, m/sec
W_{ac}	acoustic power, W
α_t	transmission coefficient
δ^*	boundary layer displacement thickness
Λ	turbulence length scale, m
ρ_0	density of sea water, use 1025 kg/m^3
ρ_1	density of material of interest, kg/m^3
σ	area density, $\sigma = \rho_1 h$, kg/m^2
ϕ	flow coefficient, $\phi = U_0/U$

INTRODUCTION

Ocean thermal energy conversion (OTEC) has been demonstrated to be a viable method for extracting stored solar energy from the world's oceans[1]. This technology is potentially useful wherever the surface water is sufficiently warm (greater than 23° C) and there is access to cold water at depth. At present thermal efficiency, seas within about twenty degrees latitude of the thermal equator are available for OTEC exploitation[2]. OTEC can be used to generate electrical power which is then transmitted to utility networks or is used to produce energy intensive products. A United States national commitment to the rapid development of this alternate energy source is reflected by public law[3]. The goal is to achieve a demonstration of at least one hundred megawatts of electrical capacity by 1986. Various OTEC configurations are possible and these are: fixed shore or near-shore facilities which have pipes extending seaward, floating plants moored in water deeper than 700 meters, and "grazing" plant-ships which are free to move and to take advantage of the warmest surface water. In all cases, warm water is collected from near the ocean's surface, and cold water must be pumped from deep depths. A typical OTEC plant will have a pipe for cold water extending to a depth of more than 600 meters. For a typical 160 MWe facility, the total volume rate of flow will be near 9×10^5 liter/sec, about one half of one per cent of the average flow of the Mississippi River at its mouth.

The OTEC plants can change the character of the ambient noise in the oceans in a way which has not previously existed. Initially, the effect will be limited to sites near shore as island communities install electrical power stations[4]. Later, plant-ships may be scattered on the open oceans to process metals, synthesize energy intensive compounds[5], or convert coal to synthetic liquid fuels[6]. It has been estimated that full, economically viable exploitation of the available thermal energy of the oceans would require more than 7000 plant-ships, each the size of a small aircraft carrier[7]. The noise radiated by these OTEC plants will be a persistent addition to the ambient noise due to shipping or natural sources.

The waterborne noise from a 1 MWe moored OTEC research facility has been measured. The results of an investigation of mechanisms for noise production and radiation are reported here along with an evaluation of the measured data.

I. General Characteristics of OTEC Plants

The basic principle of OTEC is that of a heat engine operating on the Rankine cycle with an efficiency on the order of 2.3 per cent[8]. A working fluid is evaporated to drive a gas turbine and is then condensed by the cold water. Various working fluids have been proposed and representative examples for closed-cycle plants are ammonia, propane or Freon. In an open cycle plant, water vapor powers the turbine. Most recent designs have centered around ammonia based closed cycles.

The principal components of an OTEC power plant are shown in Figure 1. Because of the low thermal efficiency of such a system, large volumes of both warm and cold sea water are required[9]. Also, the design calls for highly efficient heat-exchangers, turbines, generators and pumps. The characteristics of four moored OTEC plants are summarized in Table I. Two of these plants were built and tested[1,3,10], and the others are conceptual designs appearing in the literature[2,11,12]. In addition to the major components, OTEC plants must also have a variety of other equipment for crew habitability, ammonia purification, backup power, and biofouling control. In the case of OTEC-I research facility, the power for the pumps was derived from the propulsion turbo-generator of the ship. This implementation does not include an ammonia turbine.

II. OTEC Components as Sources of Waterborne Noise

When investigating the waterborne noise from an OTEC plant, the two questions are: what is the mechanism for noise production, and how does the noise couple to the water? There are those housekeeping functions which all plants share but which will vary greatly among designs. These noise sources are not treated here, nor is the noise due to manufacturing processes ongoing in some plants. The remaining sources of noise are: ammonia turbines, sea-water pumps, support systems associated with the energy producing cycle, and in some cases propulsion machinery for dynamic positioning of the OTEC platform. In addition, the flow of sea water past or through structures can generate noise directly.

The noise produced by the ammonia turbine is not unlike that from steam turbines in ships. The sound will exhibit tonals at the rotor-stator passing frequency, a fixed multiple of the rotation rate of the turbine. For three of the plant designs treated, these tones will occur at multiples of either 470 or 30 Hz. The directly coupled steam turbine used in the OTEC-I research ship had a rotation rate of 60 rps. Turbine and generator noise can be reduced using standard practices. Also, the requirement for high efficiency requires the designer to minimize losses due to friction and other sources. For these reasons, the contribution of these machines to the OTEC radiated noise will be assumed insignificant.

2.1 The Cold-Water Pipe

Water flowing past or through the cold-water pipe can directly generate an acoustic field. The pipe, suspended in an ocean current, will produce a vortex wake. Such wakes radiate sound as dipoles and the acoustic power radiated will depend on the sixth power of the speed of the flow[13]. The acoustic power is given by:

$$W_{ac} = (1.4X10^{-3})\ \rho_0 U_0{}^3 SM^3 \ell/b. \qquad (1)$$

The ratio of correlation length to the diameter of the pipe ℓ/b can be as low as 2 for a rigid pipe and as high as 1200 for a thin pipe free to vibrate (see list of symbols). The surface area S is the total area over which the pipe intercepts the flow. The vortex shedding sound is analogous to the sound from wires driven by the wind. The regularity of the vortex shedding process will depend on the Reynolds number (R)[14]. This number, computed with the diameter of the pipe as the length parameter, will be greater than 1×10^5 for all of the cases treated and the vortex shedding will be irregular and the noise will have a large bandwidth. The mooring cables, however, can have an associated Reynolds number $R<5 \times 10^3$ and the regular vortex shedding will produce "aeolian" tones[15]. The frequency of the tones is

$$f=S_N U_0/b.$$

The dimensionless Strouhal number S_N depends only on the Reynolds number and will be $S_N = 0.21$ for $R>1x10^3$. The vortex shedding sound power, and OTEC-I mooring cable tone frequency and level are shown in Table II for a substantial current, $U_0 = 1.5$ m/sec (3 knots). The contribution due to vortex shedding, in an ocean current, will be small. This is because of the strong dependence of the acoustic output on flow velocity. It is unlikely that an OTEC plant would be located in stronger currents[10]. Also, even though the surface current may be strong, the entire length of the pipe is unlikely to experience the same large current.

One source of noise is the turbulent boundary layer inside the pipe which results in quadrupole or dipole sources near the wall[13,16]. Of these sources, the dipole contribution will dominate and the acoustic power is given by:

$$W_{ac} \cong \pi\rho_0 (U_1 C_f' M)^3 S/6 \tag{2}$$

where C_f' is the local boundary-layer wall shear stress coefficient which is a function of the Reynolds number defined in terms of the local boundary layer displacement thickness[17]. In a smooth pipe with fully-developed turbulent flow, and for Reynolds number $R>1x10^5$,

$$C_f' = 0.012\ (U_0 a)^{-1/6}$$

from Fig. 20.1 of Ref. 14. The acoustic power generated by the turbulent boundary layer is $W_{ac}<2x10^{-5}$ for all configurations. The noise is broad-band in nature with a roll-off at $\omega = U_0/10\delta*$. This result is true only for the case where there are no trapped air bubbles. Bubbles could result from swim bladders of ingested marine organisms but it is unlikely that a significant number of these animals will occur at such depths. The cold water acts as a barrier to the descent of creatures of the deep scattering layer much below 400m[18,19]. Radiation from an elastic pipe due to flow excitation is comparable in magnitude to the noise from the turbulent boundary-layer, being somewhat more important at low frequencies[13]. The mass-loading of the wall by sea water outside the pipe will further decrease the level of the noise radiated by this means, however.

2.2 Warm and Cold Water Pumps

The interaction of large volumes of water with the pumps can be anticipated to be a major contribution to the overall noise of an OTEC plant[20]. Axial flow pumps are utilized in all OTEC configurations considered and, because of the need to maintain high efficiency, these pumps will be designed to avoid cavitation.

The interaction of the nonuniform inflow with the rotating blades results in time-dependent blade forces leading to noise[13,21]. Discrete, harmonically related tones are generated by the blades passing through steady spatial velocity nonuniformities. Turbulence results in random variations in blade loading and produces broadband noise[22,23]. The estimated magnitudes of the turbulence intensities and nondimensional turbulence length scales at the plane of the pump blade rows are tabulated in Table III. These values were estimated considering the upstream condition. The effect of a screen far upstream is to decrease the level of turbulence and this effect will depend on the resistance of the screen to flow[14].

A schematic of the flow path of cold water is shown in Figure 2 for the OTEC-I plant. This configuration is similar to that used on two of the other plants considered. The flow through the pumps of the Lockheed OTEC is shown in Figure 3. The warm-water pumps for the TRW design are downstream of the evaporators which are treated here as high resistance screens. The turbulence structure for the undisturbed ocean is based on the assumption that in the open atmosphere the magnitude of the turbulence is small and the integral length scale used is very large[14].

The theoretical spectra of the noise produced by the interaction of rotors with turbulence in the inflow have been derived by a number of authors[23,24,25,26]. No reliable method exists for estimating the spatial variations of the mean velocity at the rotor, hence the levels of the tones at the blade-passing frequency cannot be predicted with any confidence. We will concentrate on predicting the broadband acoustic power only. The theory by Sevik[24] is used to perform the prediction of the power because of its computational ease. That theory does not provide an accurate prediction of the spectrum near the frequency of the tones because it does not take into account blade-to-blade correlation of the time-dependent lift[25]. The parameters necessary to perform the calculation are listed in Table IV. Note that the TRW warm-water pump parameters are not known. However, the contribution of these pumps to the overall radiated noise is less than that due to the cold-water pumps because of the low inflow turbulence intensities for the warm-water pumps; the noise power is dependent on the square of the turbulence parameter. The spectral density of the radiated noise power is, from Ref. 24:

$$dW_{ac}/df=K\ \Lambda\ \rho_0 U^2 a^2 (1+\phi^2)^{-1} T^2 (a/\Lambda)^2 GM^3, \qquad (3)$$

$$G=F_1(r_h/a)F_2(f,\Lambda,M_0^{-1})F_3(a/\Lambda,ka),$$

$$F_1(r_h/a)^{1/2}=1-(r_h/a)^2$$

where K is a constant of proportionality. The flow coefficient ϕ is the ratio of the axial flow velocity to the tip speed of the rotor. Also, $F_2(F,\Lambda,U_0^{-1})$ is a function which defines the frequency dependence of the rotor unsteady force. The function $F_3(a/\Lambda,ka)$ defines the dependence of the radiation on the wave number scale ka and on the ratio of the turbulence length scale to the rotor radius Λ /a.

Figure 4 shows the on-axis spectra of the broad-band noise radiated by individual pumps for each of the four OTEC configurations considered. In order to obtain these spectra, the turbulence parameters associated with both the most significant eddies and those smaller scale eddies due to screens and vanes had to be estimated. The uncertainties about the turbulence experienced by the warm-water pumps preclude detailed prediction for these so only cold-water pump levels are shown. By integrating these spectra numerically, the total radiated acoustic power is obtained[27]. The range of integration was limited to 10Hz to 1kHz because the assumptions used to obtain Eq. (3) can only be satisfied when the acoustic wave length is large in relation to the dimension of the blades. The acoustic power radiated over this frequency range is given in Table I for individual pumps and also for each OTEC plant considered. The theory predicts that the radiated noise will be directional with maximum pressure fluctuation along the rotor axis[24]. The directivity decreases as the acoustic wavelength increases or as the integral scale decreases. The directivity of the radiation was taken into account when computing the total sound power.

In order to occur as waterborne noise at a distance, the noise power generated at the pump blades must couple to the sea outside of the structure within which the pumps are housed. For the Lockheed plant, the warm-water pumps couple with the surrounding ocean directly through anti-swirl vanes and a screen with small resistance to flow. The pump axes are horizontal in this case. For all of the other configurations, sea-water pumps are located in spaces which are water filled and separated from the ocean by walls of steel or concrete. The acoustic transmission coefficient depends on the surface density of the wall[13]. The ratio of incident to transmitted sound power α_t^{-1} for normal incidence is:

$$\alpha_t^{-1} = (4 + \sigma^2\omega^2/\rho_0^2 c_0^2)/4.$$

For typical designs using 35mm steel plate as hull material, the transmission loss at 1kHz is less than 1dB. Even if several compartment walls intervene, the noise generated by turbulence interaction with the pump blades will pass nearly unattenuated into the surrounding sea. For the Lockheed design, which uses concrete wall material, the transmission loss for sound traveling radially out of the cold-water sump is about 6db at 1kHz. At 100Hz, this loss is reduced to less than 1db. At frequencies less than 100Hz, the pump noise will be radiated with little directivity and will appear in the acoustic far-field as sources within 60m of the ocean's surface. At frequencies which are high enough so that the noise is transmitted through the walls less efficiently, some energy is reflected and will contribute to a reverberent sound field within the enclosure. In this case, the cold-water pipe can serve as an acoustic waveguide and radiation can occur from its lower end.

For the concrete pipe used in the Lockheed configuration, modeling predicts that the sound-pressure level at the pipe terminus is 8 to 14 dB higher than it would be if the pipe were not present. This model treats the wall material as fluid-like with no shear waves and may be somewhat inaccurate for a concrete pipe. Because of the thinner pipe walls, wall material with a characteristic impedence closer to that of water, and less direct coupling of sound to the pipes, the cold-water pipes of the other plants are unlikely to substantially alter the radiated acoustic field, even at frequencies as high as 1 kHz.

The pump noise may also excite resonances in water-filled piping. Such resonances can occur when high levels of sinusoidal driving energy are present. Resonances can lead to higher than anticipated radiation efficiency and objectionable structural vibration[28]. For the cold-water pipes, the "organ-pipe" resonance fundamentals occur at frequencies of 0.6 to 1.2 Hz[29]. These resonances will be subdued because the pipes are not ideally stiff but the resonant response could be bothersome if the blade-passing frequency coincides with a small multiple of the fundamental. Similar resonances can occur in portions of the system for ingesting warm water or in pipes for outflow. All such resonances should be avoided, however, because of potentially damaging levels of vibration[28].

The noise field due to the interaction of turbulence with the pump blades is due to the rigid-body response of the blades. The reaction of the blade unsteady forces through the rotor drive shaft may excite response modes in the structure of the plant much as marine propulsors cause hull flexing or local modes of vibration in ships[30]. Such resonances can cause increased radiation of sound but they are considered of little importance in evaluating the noise from an OTEC plant. This is because such vibrations are undesirable and efforts will be made to decrease their magnitude. Resonances which do occur will most likely occur at frequencies which are the same as, or near, the blade-passing frequencies of the pumps[30].

2.3 Other Equipment

In a typical OTEC plant, there will be a number of pumps associated with the transport of liquid ammonia. Motor armatures, pump impellers, and gears, when they are present, will produce line-component spectra with the tones occurring at the fundamental rotation rate or at the gear-mesh rate and harmonics of these rates[27]. The volume of ammonia which must be handled is large (6000 kg/sec for the Lockheed plant[2]) and the associated machines could be significant sources of noise. The possible sources of noise are so numerous, however, and the relative contribution of each source is so variable that the far-field noise due to these sources has not been estimated.

The motors powering the sea-water pumps are large and therefore potentially significant sources of tones. For the plants considered, three of them have these motors well above the water line and coupling to the water is primarily by means of vibration transmitted through the structures of these plants. Vibration isolation can significantly reduce this source of noise. In the Lockheed design, the motors are located in pods in the flow of sea water and they are geared to the pumps. This design is less amenable to noise quieting and tones corresponding to the motor rate and the rate of gear meshing are likely to be radiated.

Thrusters or propulsors used for dynamic positioning of the OTEC platform can produce a significant amount of propeller noise[13,27]. Of the four plants considered, only the OTEC-I design incorporated such thrusters and they were located some 8.5 m below the surface. By comparing these thrusters with marine propellers of similar size, it is likely that the thrusters will cavitate at rotation rates of 0.8 to 1.5 rps[27]. Cavitation noise is broad-band in nature and will have a peak between 150 and 500Hz for this size propeller.

The low efficiency of the OTEC process requires that the surfaces of the evaporators and condensors which are in contact with sea water be kept scrupulously clean. Low-level chlorination is one technique for reducing the levels of fouling by marine ogranisms[2]. The equipment needed for chlorination are small pumps and electrolytic generators which are not likely to contribute significantly to the radiated noise. Another cleaning method uses small sponge-rubber balls which are introduced upstream of the evaporators or condensors and are then recovered from the outflow for storage or to be re-circulated[10]. This biofouling control system would be used intermittently. Noise may be generated by this process because of velocity fluctuations in the flow resulting from the varying friction forces as the balls move through the tubes of the evaporator or condensor. This is indeed a complex process and acoustic measurements may be the only means for evaluating the significance of this source of noise.

III. Measurements of the Waterborne Noise from OTEC-I

During the winter of 1980-81, and into the spring of 1981, the Department of Energy OTEC research facility, the SS Ocean Converter, was moored near Keahole Point, Island of Hawaii. This plant was called OTEC-I and it was designed to test various aspects of the OTEC process. Figure 5 shows the location of OTEC-I along with the bottom topography, prevailing near-surface current and surface winds at that site[31]. The combined effect of the current, wind and ocean swell was to cause the converted navy tanker to move around the moor. Two trainable thrusters served to dynamically orient the hull for satisfactory sea-keeping and the turbo-electric drive system of the tanker was used to power the thrusters as well as the sea-water pumps.

A three phase measurement of the noise due to the OTEC-I facility was conducted. This consisted of an airborne noise survey and two subsequent phases during which the waterborne noise was recorded. During the airborne noise survey, all machines suspected of being sources of noise were photographed and the location and equipment parameters noted. At that time, the OTEC cycle was fully operational at a power level of 41MWt. The power in the ammonia cycle was dissipated by a throttle valve which produced a high level of insonification of the OTEC machinery compartment. This source of noise is one which would not exist in an OTEC plant designed to deliver useful power. During the waterborne noise recording phases, the ammonia cycle was not operating and the evaporator and condensor were nitrogen filled. This setup eliminated the noise due to the throttle valve but also removed the noise contributed by three pumps used to transport liquid ammonia. These were low power pumps, however, and their contribution to the overall radiated noise would probably be minor.

Phase 2 of the measurement was conducted on 1 April 1981. During this phase, the rates of flow of water through the pumps for warm and cold water were changed and the speeds of the main and auxiliary turbo-generators were varied. The schedule of operating conditions is shown in Table VII. By varying the speed of the main turbo-generator, it was possible to identify the tones associated with many of the auxiliary systems which are synchronous with the power-line rate. The third phase of the measurement was necessary because of equipment problems during Phase 2 which precluded calibration of the spectral levels. Phase 3 was conducted on 10 April 1981 and other commitments precluded altering conditions onboard the converted tanker. The only biofouling control method used at any time during these phases was low-level chlorination.

The waterborne noise was collected using ambient noise monitoring buoys deployed from an aircraft. The initial location of the buoys was chosen so that the current would carry them near the SS Ocean Energy Converter. Figures 6 and 7 show the initial position of the buoys relative to the platform and the motion of some of the buoys during the recording sessions. The buoys were tracked using radio direction finding equipment in the aircraft and in some cases they were visually observed from the ship's bridge. The buoys had a calibrated broad-band response of 10 Hz to above 10 kHz and they were preset to deploy the hydrophone to either 18 or 91 m. The acoustic signals were recorded aboard the aircraft using a precision 14 channel, wide-band recorder. In addition, a high resolution, multi-channel spectrum analyzer with hard-copy output was used in the aircraft to monitor the signals from the buoys. Bathy-thermograph buoys were also dropped so that the sound-velocity profile could be obtained for the days of the recording sessions (see Figure 8). The ambient noise consisted of a number 2 to 3 sea-state (Beaufort number) at the location of the OTEC-I and over a broad sector to the north-northeast clockwise to the southwest. High surface winds and breaking seas existed in the Alenuihaha channel at least 10 km distant to the northwest and west. The whole area is one of sparse shipping traffic and only an occasional small fishing boat approached closer than 5 km.

Data reduction consisted of narrow-band spectrum analysis with spectrum averaging. No correction was attempted for Lloyd mirror effects but the data were averaged over a sufficiently long time interval so that the variability of the measurements was small, less than 2dB (50% confidence interval) in most cases. Propagation loss correction was based on acoustic modeling for direct-path propagation between the ship and the buoys. The data were compared between different buoys at the same depth, buoys equidistant from the ship and at different depths, and for the same buoy at different times. Comparisons of the overall spectral characteristics for similar plant conditions during the two waterborne noise measurements show excellent agreement.

On 13 April 1981, the SS Ocean Energy Converter was disconnected from the cold-water pipe and left the moor. That aspect of the Department of Energy research has been discontinued and the ship is a member of the inactive fleet, anchored in Pearl Harbor. Some of the equipment has been removed for reuse at the University of Hawaii Seacoast Test Facility on the island of Hawaii.

The noise radiated by OTEC-I at low frequencies is shown in Figures 9 and 10. These spectra are typical of the recorded data and show narrow and stable tones which are associated with the rate of passage of the blades. Because the precise rate of rotation of the pumps was not available, the harmonic relationship cannot be accurately determined from the few tones detected. All tones which can be identified with the pumps for warm and cold water occur at frequencies less than 25 Hz. In the OTEC-I configuration there is also a pump for discharging the mixed water overboard. This pump was only powered to a small fraction of its rated capacity and was not identifiable in the radiated spectrum. Other pronounced narrow-band components are due to the turbo-generator, auxiliary equipment, or thrusters. The thrusters were both operated at about 1.7 rps.

The overall estimated spectrum for broadband noise radiated by the OTEC-I facility is shown in Figure 11. This spectrum has been adjusted for propagation loss and sensor sensitivity to yield normalized source spectrum levels. The spectra, as collected from various buoys, does not show any systematic dependence on sensor depth. At the higher frequencies, the 60 Hz turbo-generator tone and its harmonics dominate. Several unstable tones were identified as resulting from equipment in the steam plant.

By comparing the spectrum from a distant buoy to that from buoys within 1km of the OTEC-I facility, it was found that the radiated broadband energy in the range of frequencies from 40 Hz to just below 60 Hz is low and most likely to be masked by ambient noise. The 50 per cent error bound on the estimated broadband spectrum shown in Figure 11 reflects the uncertainty in estimating these levels. There is also evidence to suggest that ambient noise dominated at frequencies greater than about 400 Hz.

IV. Discussion

The prediction of the waterborne noise from OTEC plants identifies the noise due to the interaction of inflow turbulence with the sea-water pumps as a significant broadband source. Also, thrusters, when used for dynamic positioning of the platform, will produce broadband noise which may dominate at frequencies exceeding 70 to 100 Hz. While the noise due to vortex shedding can be another broadband source, the strong dependence on the ocean current at the site, and the difficulties of deploying a cold-water pipe in a substantial current suggest that this source will not be important in most situations. There are many potential sources of narrow-band energy and the prediction of the spectrum levels associated with these sources was not attempted. At the lower frequencies of 10 to 25 Hz, sea-water pump related tonals may dominate. At higher frequencies, the tones due to a variety of rotating machinery will produce a complex narrow-band spectrum not unlike that produced by a ship. There are some potential sources of noise for which no prediction was possible. Data for some of these, such as the biofouling control systems, may only be available through measurements.

The only OTEC plant for which waterborne noise data are known to exist is the OTEC-I facility which is no longer in operation. The data collected from this facility suggest that an individual OTEC plant is likely to be a benign contributor to the ambient noise in the ocean. In Figure 11, the radiated broadband noise from the OTEC-I plant is compared to the predicted spectrum for the noise due to turbulence interaction with the axial-flow pumps. Also shown in Figure 11 is an interpolation of the predicted broadband noise due to the thrusters. This is the spectrum for a small marine propeller which has been adjusted for static pressure and rotation rate[27]. The cavitation spectrum of such a propeller was used because the thrusters were located below the keel and were smaller than are the propellers for most surface ships for which data are available. It appears that the noise due to the thrusters dominates the broadband spectrum at frequencies above about 70 Hz. Since the cavitation spectra given in Ref. 27 do not extend lower than 50 Hz, it cannot be determined if the thruster broadband noise or the noise due to the sea-water pumps is more significant at frequencies from 10 to 50 Hz. In any case, the observed broadband spectrum due to the pumps does not exceed predicted levels by more than 10 dB. The observed data place an upper bound on the noise which is radiated by the pumps.

The predictions suggest that the cold-water pipe will have little effect on the acoustic field due to an OTEC plant. This is expected to be especially true for the thin-walled polyvinylchloride pipe like that used with OTEC-I. There was no indication from the measured data that pipe resonances, or channeling of the sound by the pipe occurred. The available transducer depth may not have allowed detection of vertical structure in the radiation pattern, however.

V. Conclusions

The pump induced broadband waterborne noise from four moored OTEC plants has been predicted. The spectrum predicted for a 1MWe plant, OTEC-I, was compared with measured data. The measurements show that the noise contributed by the interaction of turbulence with the sea-water pumps is no more than 10 dB higher than predicted at low frequencies. The broadband noise due to thrusters used for dynamic positioning of the platform dominates at frequencies greater than about 70 Hz.

On the basis of the prediction, it is concluded that a 160 MWe OTEC plant will radiate less than 0.05 acoustic Watts of broadband sound power in the frequency range of 10 Hz to 1 kHz. This is the sound power for a plant which has no provisions for dynamic positioning. The plant will also radiate tonal energy and this radiation will be concentrated at the blade-passing frequency of the sea-water pumps, at the 30 Hz turbine rotation rate and harmonics thereof, and at other frequencies corresponding to the rotation rate of auxiliary pumps and motors. Radiation will be similar to that from a near-surface source and the effect of the cold-water pipe will be insignificant at frequencies less than 100 Hz, and small at 1kHz. Resonances in water-filled piping should be avoided because of the potentially damaging vibration which will occur at these resonances.

The predicted broadband power radiated by even a large OTEC plant (>100MWe) is at least an order of magnitude less than that which is radiated by a typical ocean-going freighter[13,27]. However, the large number of these plants which may ultimately operate in tropical waters can significantly alter the ambient noise characteristics in an area of the world which is now acoustically quiet. Also, an OTEC plant operating near an acoustic calibration facility has the potential for causing persistent acoustic interference. The implementation of OTEC plants can raise concerns on the part of the Department of Defense because of such interference[32].

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Table I. General characteristics of four OTEC plants.

	Mini-OTEC	OTEC-I	TRW/ [e] Global Marine	Lockheed [h]
design net power (MWe)	0.018	1.0	100.0	160.0
design gross power (MWe)	0.053	- [d]	UNK [f]	260.0
warm-water flow (l/sec)	126 [b]	5210	UNK	3.52×10^5
cold-water flow (l/sec)	126	4300	3.8×10^5 (c)	4.52×10^5
evaporator/condensor type	titanium plate	titanium shell and tube		
turbine speed (rps)	470	-	4 @ 30	4 @ 30
cold-water pipe				
length (m)	671	640	1220	610
inside diameter (m)	0.56	3 @ 1.22	15.3	31.1 [i]
seawater velocity (m/sec)	0.5 [c]	2.1	2.0 [g]	2.4
warm-water pump (hp) [a]	19	409	UNK	16 @ 1630
cold-water pump (hp)	27	460	UNK	16 @ 4090
platform	barge	modified tanker	floating disk	spar buoy

[a] metric horsepower for given flow rate, [b] estimated nominal flow rate, [c] not reported, estimated by authors, [d] OTEC-I did not have an ammonia turbine installed, [e] see Refs. 11 and 12, [f] data not provided, [g] assumed value, [h] see Ref. 2, [i] minimum diameter of a stepped diameter pipe.

Table II. Noise due to vortex shedding from the cold-water pipe or the mooring cable in an ocean current.

	Mini-OTEC	OTEC-I	TRW/GM	Lockheed	OTEC-I moor [a,b]
correlation length used, ℓ/b	300	150	50	3	1500
Aeolian tone					
flow velocity (m/sec)					0.125
Strouhal number, S_N					0.21
frequency (Hz)		- not likely -			0.34
spectral level re 1 μPa/1m					< 100dB
vortex shedding noise (W_{ac}) [c]	5.5×10^{-4}	1.0×10^{-3}	4.5×10^{-3}	3.0×10^{-4}	1.4×10^{-10}

[a] see Ref. 15, [b] l=915m, d=0.13m, [c] this is the upper limit for this source at a current of 1.5 m/sec over the total length of the pipe.

Table III. Pump inflow turbulence parameters for four OTEC plants.

pump	upstream condition	turbulence parameter T	nondimensional turbulence integral length scale R/Λ primary	secondary
Mini-OTEC				
warm water	undisturbed ocean 3m below surface, trash screen, sump	0.005	UNK	15
cold water	fully turbulent pipe flow, screen	0.05	1.0	15
OTEC-I				
warm water	undisturbed ocean 6m below surface, stand-pipe, screen, sump	0.01	UNK	95
cold water	turbulent pipe flow, moon pool, screen	0.05	1.0	95
TRW/GM				
warm water	undisturbed ocean 8m below surface, trash screen, evaporator	0.005	0.03	-
cold water	fully developed pipe flow, screen, moon pool, developing pipe flow	0.06	1.0	-
Lockheed				
warm water	undisturbed ocean 46m below surface, screen, antiswirl guidevanes	0.04	UNK	20
cold water	fully turbulent pipe flow, guidevanes	0.09	1.0	20

Table IV. Pump parameters for calculating the noise due to turbulence, blade interaction.

	Mini-OTEC	OTEC-I	TRW/GM	Lockheed
flow rate (l/sec)				
warm-water pump	1.3×10^2	4.3×10^3	UNK	2.1×10^4
cold-water pump	1.3×10^2	5.2×10^3	9.5×10^4 (c)	2.8×10^4
number of pumps (WW,CW)	1,1	1,1	4,4	16,16
propeller diameter (m)				
warm-water pump	0.3 [a]	1.1 [c]	UNK	6.1
cold-water pump	0.3	1.4	4.88 [c]	6.1
propeller speed (rps)				
warm-water pump	29.3	4.68	UNK	0.73
cold-water pump	29.3	4.93	1.1	1.1
number of blades per pump	3 [a]	3	12 [d]	2
hub diameter (m)				
warm-water pump	0.1 [a]	0.4 [c]	UNK	3.1
cold-water pump	0.1	0.6	1.2	3.1
flow velocity, U_0 (m/sec)				
warm-water pump	0.4 [b]	2.9 [b]	UNK	3.9
cold-water pump	0.4 [b]	2.1 [b]	5.4 [d]	5.2
blade angle (°)				
warm-water pump	19 [b]	19 [b]	UNK	18
cold-water pump	19 [b]	19 [b]	21 [d]	16
propeller chord (m)	0.17 [b]	1.0 [b]	1.2 [d]	3.4 [e]

[a] data provided by Worthington Pump Corp., [b] not reported, estimated by authors, [c] data provided by Rockwell International, [d] data provided by Department of Energy, [e] estimated from diagram in Ref. 2.

Table V. Summary of noise contributed by the turbulence induced acoustic field of the axial flow pumps of four representative OTEC designs.

Acoustic power in band 10 Hz to 1 kHz	Mini-OTEC	OTEC-I	TRW/GM	Lockheed
		(W_{ac})		
For individual pumps				
cold-water	1.0×10^{-2}	1.0×10^{-4}	3.2×10^{-3}	2.3×10^{-3}
warm-water	$< 1 \times 10^{-3}$	$< 2 \times 10^{-5}$	$< 5 \times 10^{-4}$	$< 5 \times 10^{-4}$
Total turbulence induced pump noise				
all cold-water pumps	1.0×10^{-2}	1.0×10^{-4}	1.3×10^{-2}	3.7×10^{-2}
all warm-water pumps	$< 1 \times 10^{-3}$	$< 2 \times 10^{-5}$	$\leq 2 \times 10^{-3}$	$< 8 \times 10^{-3}$
all pumps	$< 1.1 \times 10^{-2}$	$< 1.2 \times 10^{-4}$	$< 1.5 \times 10^{-2}$	$< 4.5 \times 10^{-2}$

Table VI. Characteristics of the cold-water pipes of four OTEC plants. Unless otherwise noted, sound velocity values are for longitudinal waves, measured at ultrasonic frequencies.

	Mini-OTEC	OTEC-I	TRW/GM	Lockheed
thickness of cold-water pipe (m)	0.02	0.03	0.13	0.33
material	high density polyethelene	poly-vinylchloride	glass reinforced plastic	concrete
density, ρ_1 (kg/m^3)	950 [a]	1380 [b]	1200 [d]	2600
velocity, C_1 (m/sec)	2560 [a]	1520 [c]	2500 [d]	3100
area density, σ(kg/m^2)	19	41	156	858

[a] D. L. Folds, J. Acoust. Soc. Am., 52, 426 (1972), [b] average value, Handbook of Chemistry and Physics (Chemical Rubber Publishing Co., Cleveland Ohio 1958), [c] measured at 500 Hz, data provided by L. Ho, David Taylor Naval Ship Research and Development Center, Annapolis Md., [d] data provided by W. Madigosky, Naval Surface Weapons Center, Silver Spring Md.

Table VII. Conditions on board the SS Ocean Energy Converter during Phase 2 of the measurement on 1 April 1981.

Time (HI Std)	Cold-water flow rate (l/sec)	Warm-water flow rate (l/sec)	Main turbo-generator (rps)	Aux. turbo-generator (rps)
1225	4050	5680	60.3	19
1245	4050	5680	62.0	19
1255	4050	5680	62.0	21
1305	4050	5680	62.0	19
1307	4050	5680	60.3	19
1322	2840	5680	60.4	19
1408	4050	3410	60.4	19
1426	4050	3410	62.2	19
1446	4050	3410	60.4	19
1506	3920	5340	60.2	19
1530	3920	5340	60.2	19

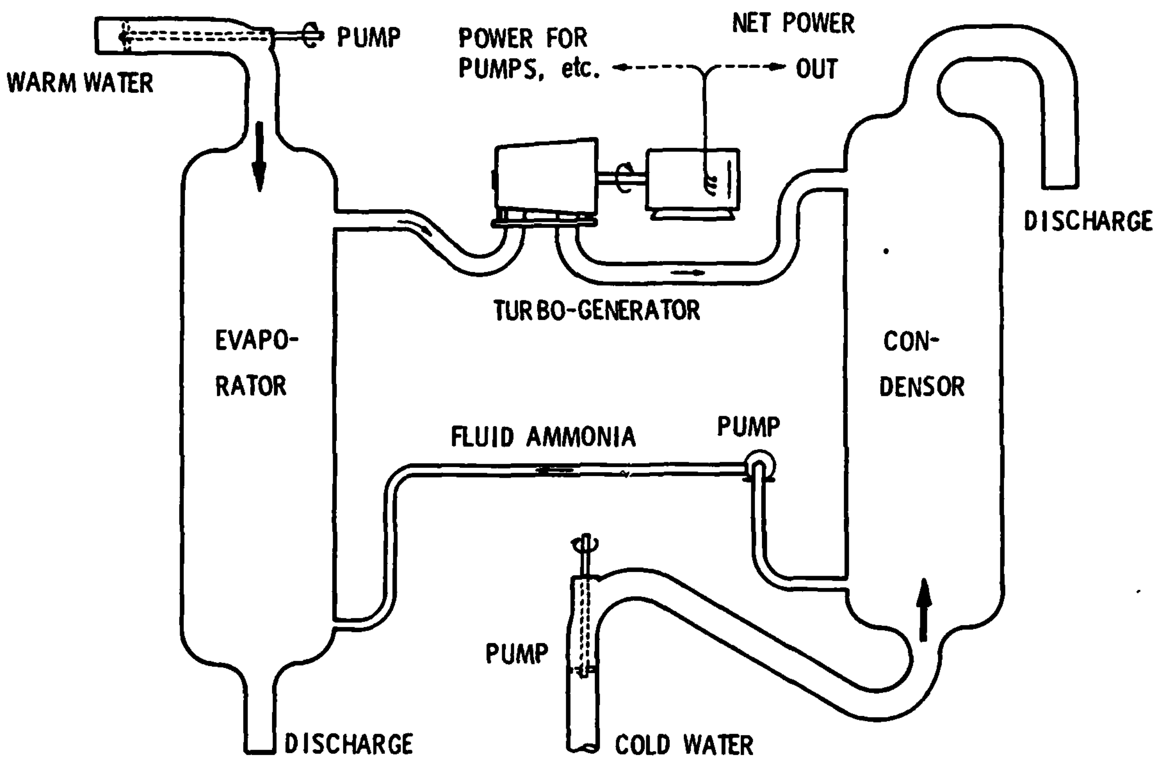

Figure 1. Schematic diagram of a closed-cycle Ocean Thermal Energy Conversion plant using ammonia as a working fluid.

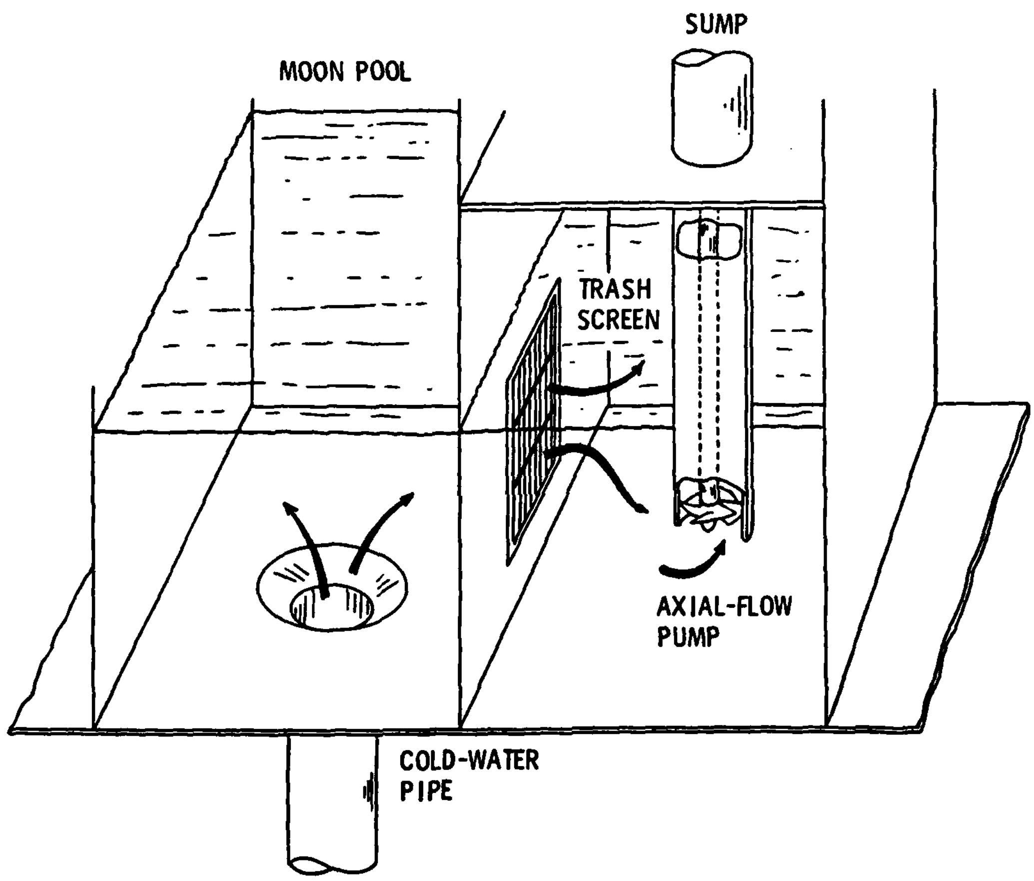

Figure 2. Schematic diagram showing the flow of sea water into the cold-water pump for the OTEC-I configuration. The moon pool is open above, the sump is enclosed.

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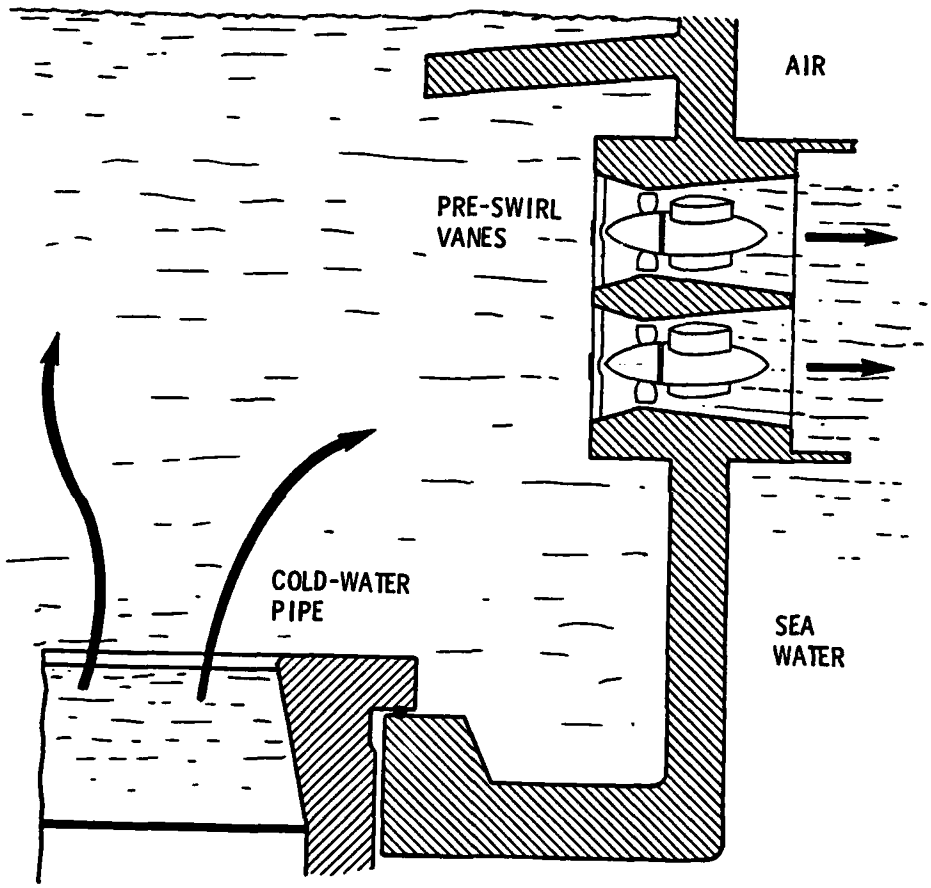

Figure 3. Diagram showing the flow of cold water through the pumps of the Lockheed conceptual plant. Each pump module consists of four pumps in a cluster.

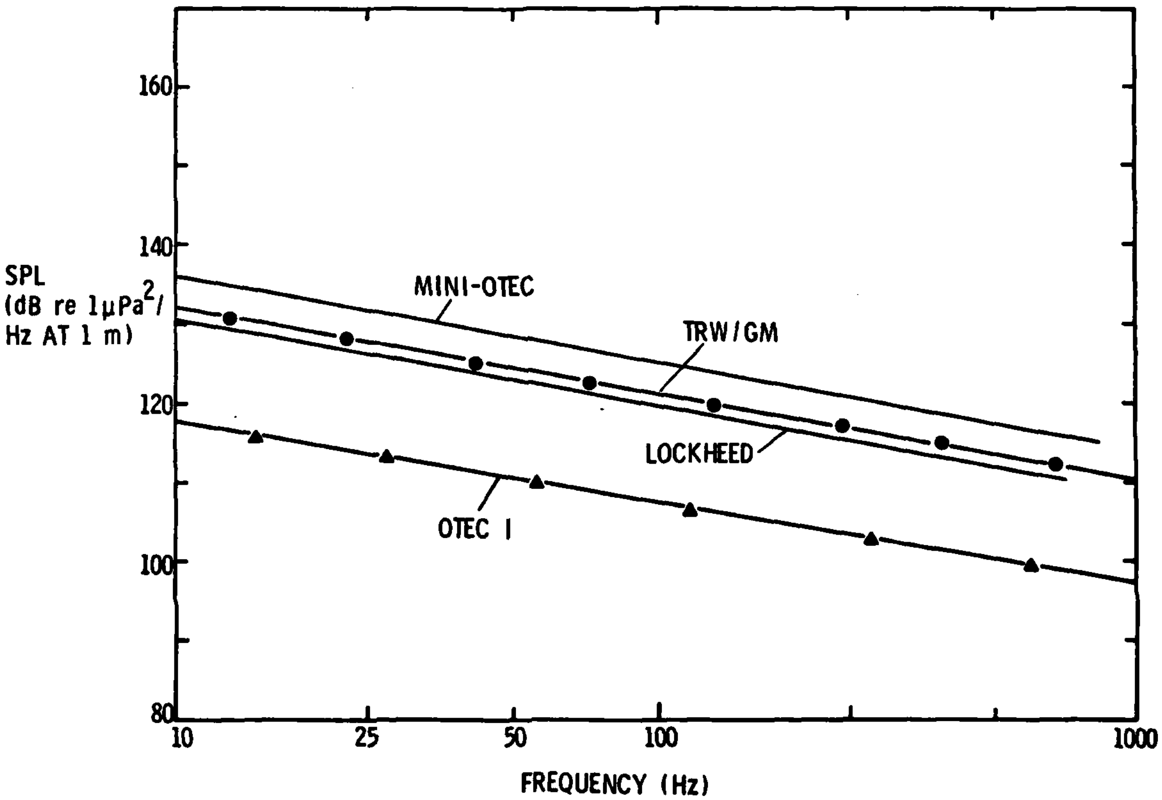

Figure 4. Predicted radiated broadband noise from individual pumps for the OTEC plants considered.

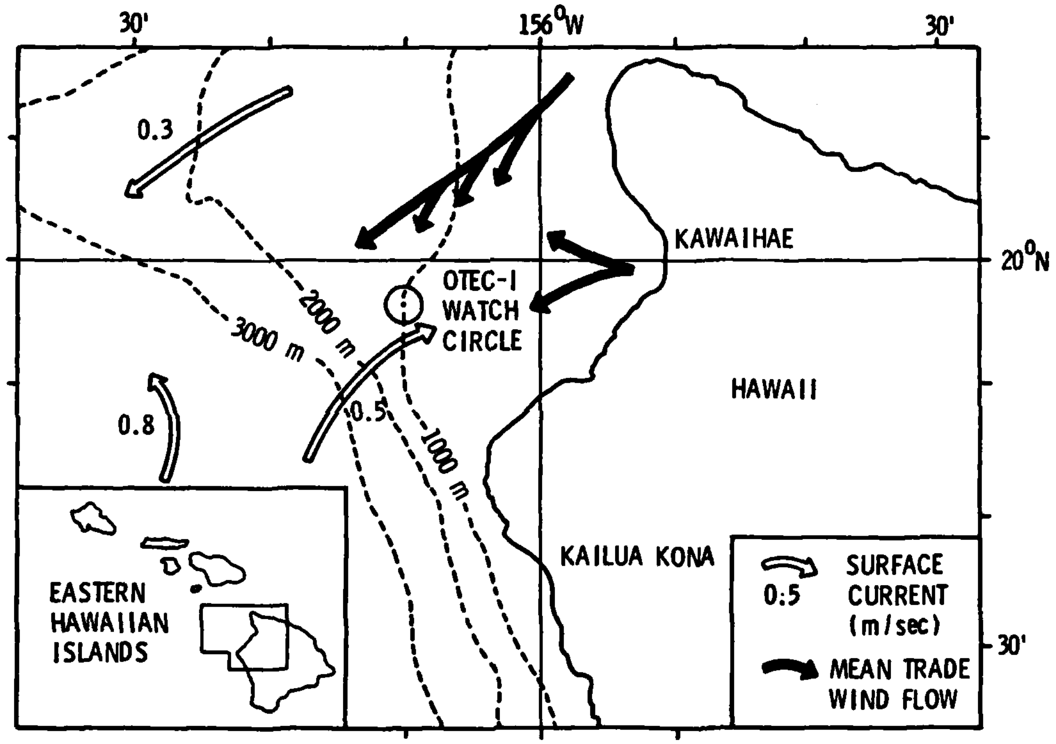

Figure 5. Location of OTEC-I in the vicinity of the island of Hawaii showing the bottom topography, near-surface current, and surface winds.

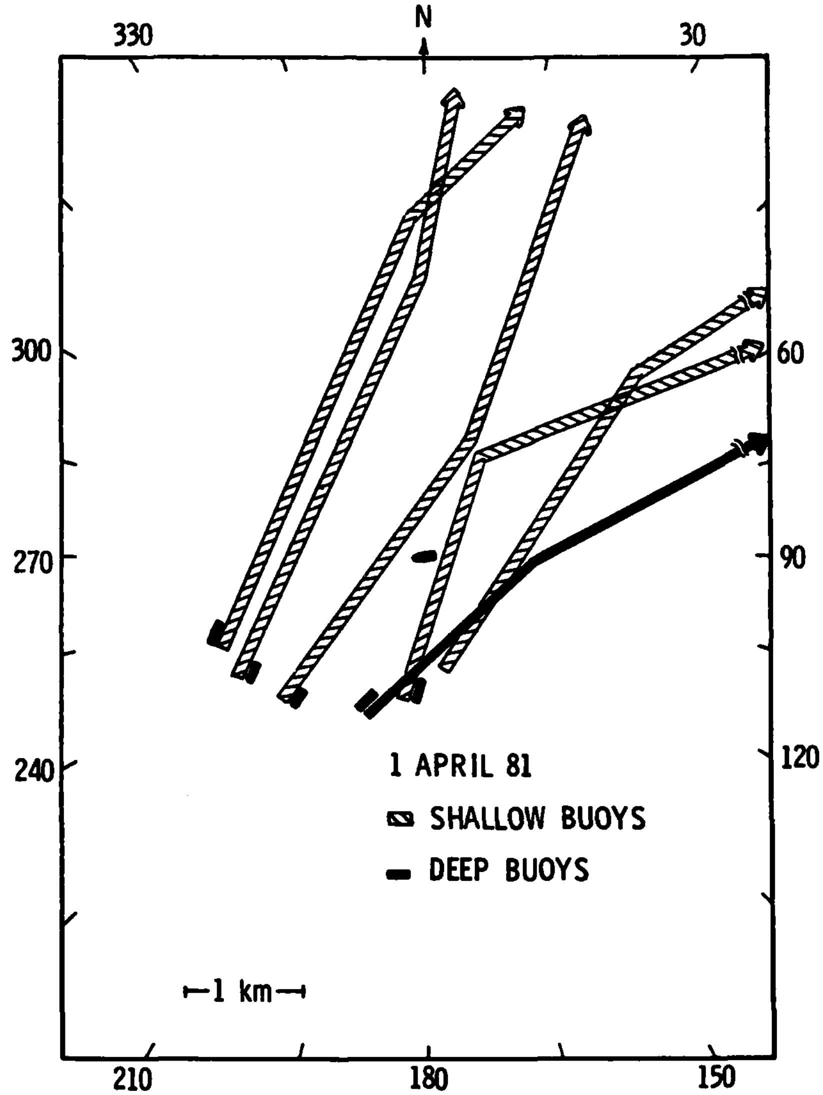

Figure 6. Sound recording buoy initial locations and drift during Phase 2 of the measurement on 1 April. Buoys for which the drift is not shown were not tracked.

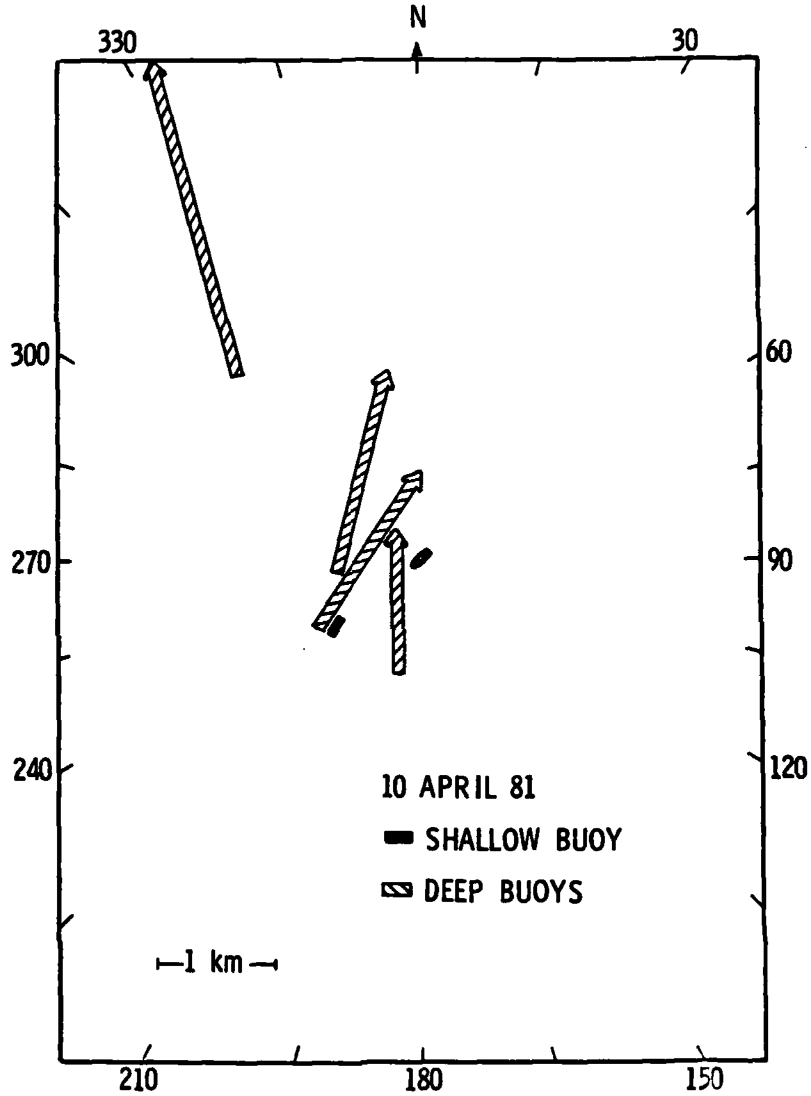

Figure 7. Initial locations and drift of sound recording buoys during Phase 3 of the measurement on 10 April. The shallow buoy was not tracked after deployment.

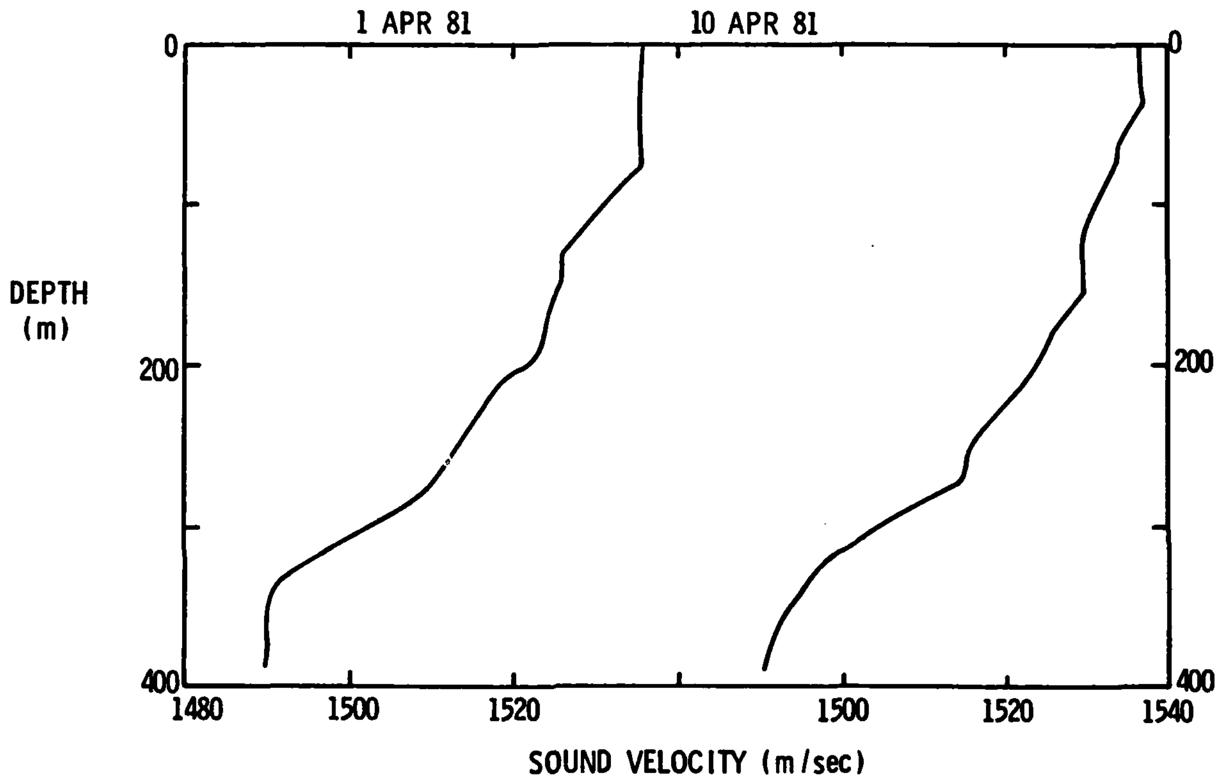

Figure 8. Sound velocity profiles measured at the OTEC-I site on the days of the waterborne noise collection.

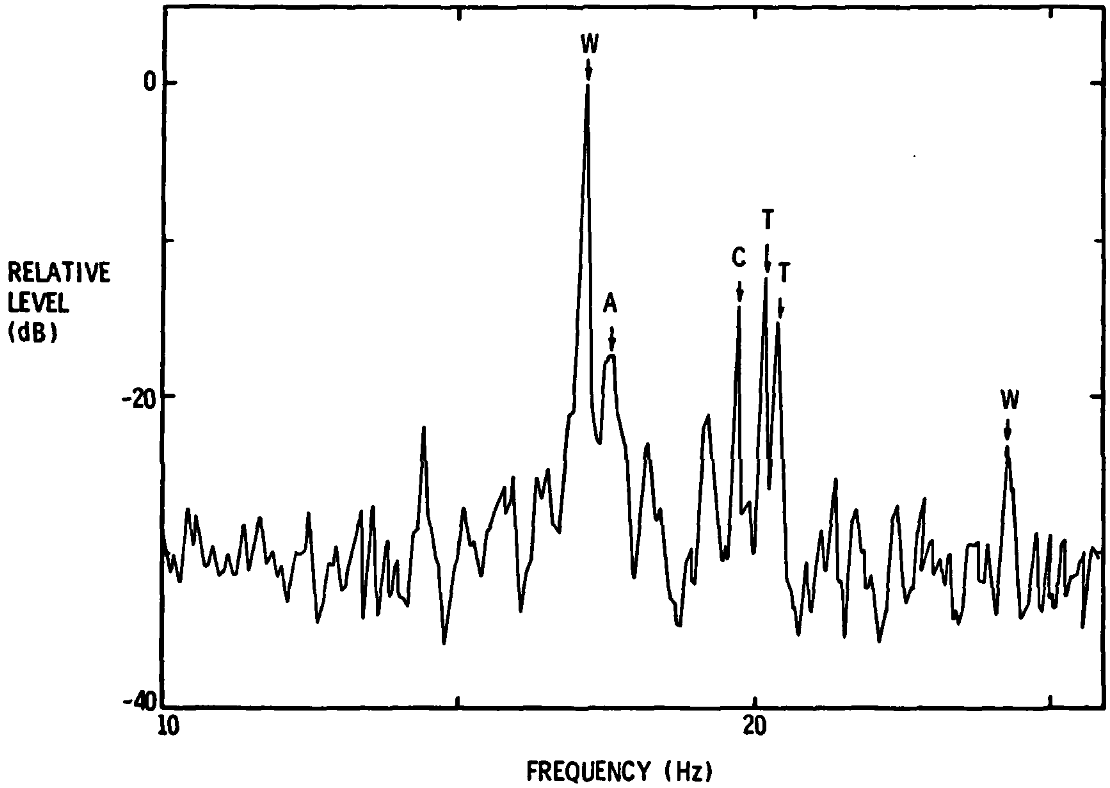

Figure 9. High resolution relative radiated noise spectrum for OTEC-I operating at maximum power level, 41 MWt. Average of 128 instantaneous spectra, analysis bandwidth is 0.0488 Hz. A-known auxiliary, C-cold-water pump harmonic, T-thruster harmonic, W-warm-water harmonic.

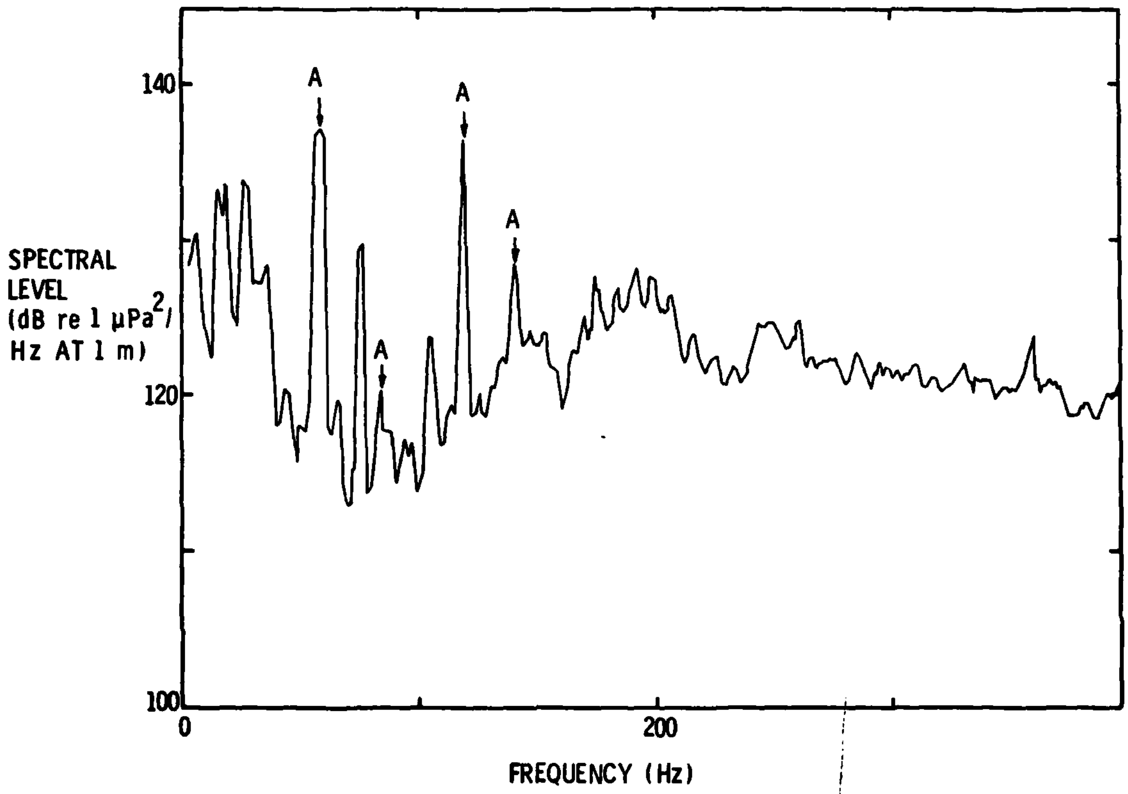

Figure 10. Sound pressure spectrum for the OTEC-I facility. Collected by a deep buoy at a range of about 1km. Average of 64 instantaneous spectra. A-known auxiliary equipment tonals.

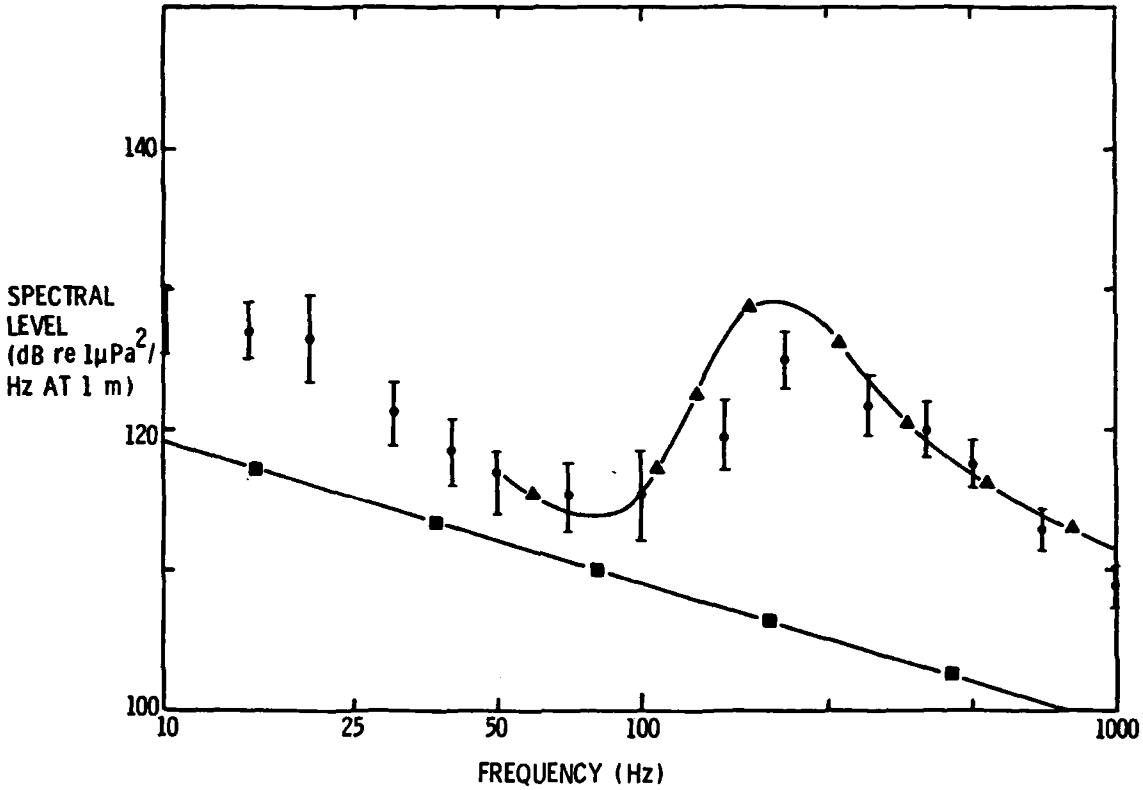

Figure 11. Estimated broadband sound pressure spectrum and theoretically derived source spectrum. ●-measured and 50 percent confidence bound, ■-predicted waterborne noise spectrum due to turbulence interaction with the cold-water pump, ▲-predicted noise due to thrusters used for dynamic positioning.

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