The MIT Marine Industry Collegium
Opportunity Brief #15

Wave Power Systems

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PREFACE

This Opportunity Brief and the accompanying Workshop (held on January 16, 1979) were presented as part of the MIT/Marine Industry Collegium program, which is supported by the NOAA Office of Sea Grant, by MIT and by the more than 90 corporations and government agencies who are members of the Collegium. The underlying studies at MIT were carried out under the leadership of Professors Carmichael, Mei, and Pleass, but the author remains responsible for the assertions and conclusions presented herein.

Through Opportunity Briefs, Workshops, Symposia, and other interactions the Collegium provides a means for technology transfer among academia, industry and government for mutual profit. For more information, contact the Marine Industry Advisory Services, MIT Sea Grant, at 617-253-4434.

Norman Doelling

1 July, 1979

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1.0 A Business Perspective

Anyone who has been on a coastline or at sea during a storm has an intuitive feeling for the immense quantity of energy represented by ocean waves. In an energy conscious era, it is a short step to considering the possibility of profitably capturing, converting and using that energy.

Some relatively simple calculations coupled with historical observations of wave height and wave period confirm that the average power of ocean waves is large - e.g., measured in kilowatts to tens of kilowatts per meter of wave front. Moreover, the power density is high compared with wind or solar energy. So indeed ocean wave power is worth investigating as a useable, renewable, alternative energy source (References 1, 2, 3).

Research projects at the University of Delaware and MIT are addressing several interesting aspects of wave energy absorbers and converters. Professor Michael Pleass of the University of Delaware has been studying the use of wave energy to power mechanical sea water pumps for reverse osmosis desalination systems (Reference 6).

Professor Douglas Carmichael of MIT has carried out a program to confirm and extend the theoretical and experimental work of Professor John Salter on energy conversion devices now known as "Salter Cams" or "nodding ducks" (Reference 5). Carmichael's cost estimates for building such a system at two representative locations off the Northeast Coast of the U.S. highlight problems related to the need to constrain large mooring forces and to attendant mooring costs. An alternative conversion device known as the Cockerell raft has been investigated by Professor

C.C. Mei of MIT and one of his doctoral students, Pierre Haren (Reference 4). This approach appears to obviate many of the problems Carmichael raises concerning Salter cams.

A slightly oversimplified summary suggests that both Salter cams and Cockerell rafts can be designed to convert wave motion to relative mechanical motion and mechanical forces. Mooring problems and costs suggest Salter cams will be much more expensive than Cockerell rafts. A major problem is converting the available mechanical power to a more useful form, i.e., hydraulic or electric power.

Opportunities abound for companies that have the engineering ingenuity needed to convert the rotary motion of a cam or the angular displacement of two rafts into useable electrical or hydraulic power.

Additional opportunities will be available to shipbuilders or manufacturers of offshore equipment who could build the cams or rafts.

The primary intent of this Brief is to put more certain upper limits on the amount of power that can be extracted from waves and somewhat more certain lower bounds on some costs.

Based on Professor Carmichael's cost analyses and on the apparently lower costs of Cockerell rafts as described by Professor Mei, wave energy devices should be possible in the sizes and costs which Professor Pleass suggests are necessary for economically viable desalination systems. Moreover, work done recently (after the Collegium workshop on January 16, 1979, at which wave power was discussed) by Professor J. N. Newman of the MIT Ocean Engineering Department lends additional support for the efficacy of slender Cockerell rafts. This work will be published in a forthcoming issue of "Applied Ocean Research."

2.0 The Salter Cam System

A Salter cam is depicted graphically in Figure 2.1. The asymmetrical shape causes the cam to "rock" about the roll axis when an incoming wave impinges. By appropriate design of the cross-section of the cam and the moment of inertia of the cam, the natural frequency of the rocking cam can be made equal to the natural frequency of the arriving waves and very efficient wave energy absorption can be obtained.

Table 2.1, taken from Reference 5, indicates the average amounts of power available from waves for each meter of wave crest when averaged over an entire year. Significant wave heights ($\overline{H}_s$) are in meters, periods ($\overline{T}$) are in seconds, and average powers ($\overline{P}$) are in kilowatts/meter (or Megawatts per kilometer!).

TABLE 2.1

WAVE CLIMATOLOGY NEAR U.S. COASTS

Significant Wave Height, $\overline{H}_s$, Period, $\overline{T}$, and Wave Power, $\overline{P}$, Averaged Over All Seasons

	COASTAL			DEEP OCEAN		
	$\overline{H}_s$ m	$\overline{T}$ s	$\overline{P}$ kw/m	$\overline{H}_s$ m	$\overline{T}$ s	$\overline{P}$ kw/m
North Atlantic	1.0	8.5	5.2	3.2	6.3	37.1
Mid Atlantic	.8	7.9	3.1	2.7	5.9	25.6
South Atlantic	.7	6.7	2.5	2.4	6.0	22.1
North Pacific	---	---	---	3.4	11.0	81
Mid Pacific	1.0	10.4	5.7	2.6	10.3	52
South Pacific	.9	13.2	4.9	2.1	13.2	25

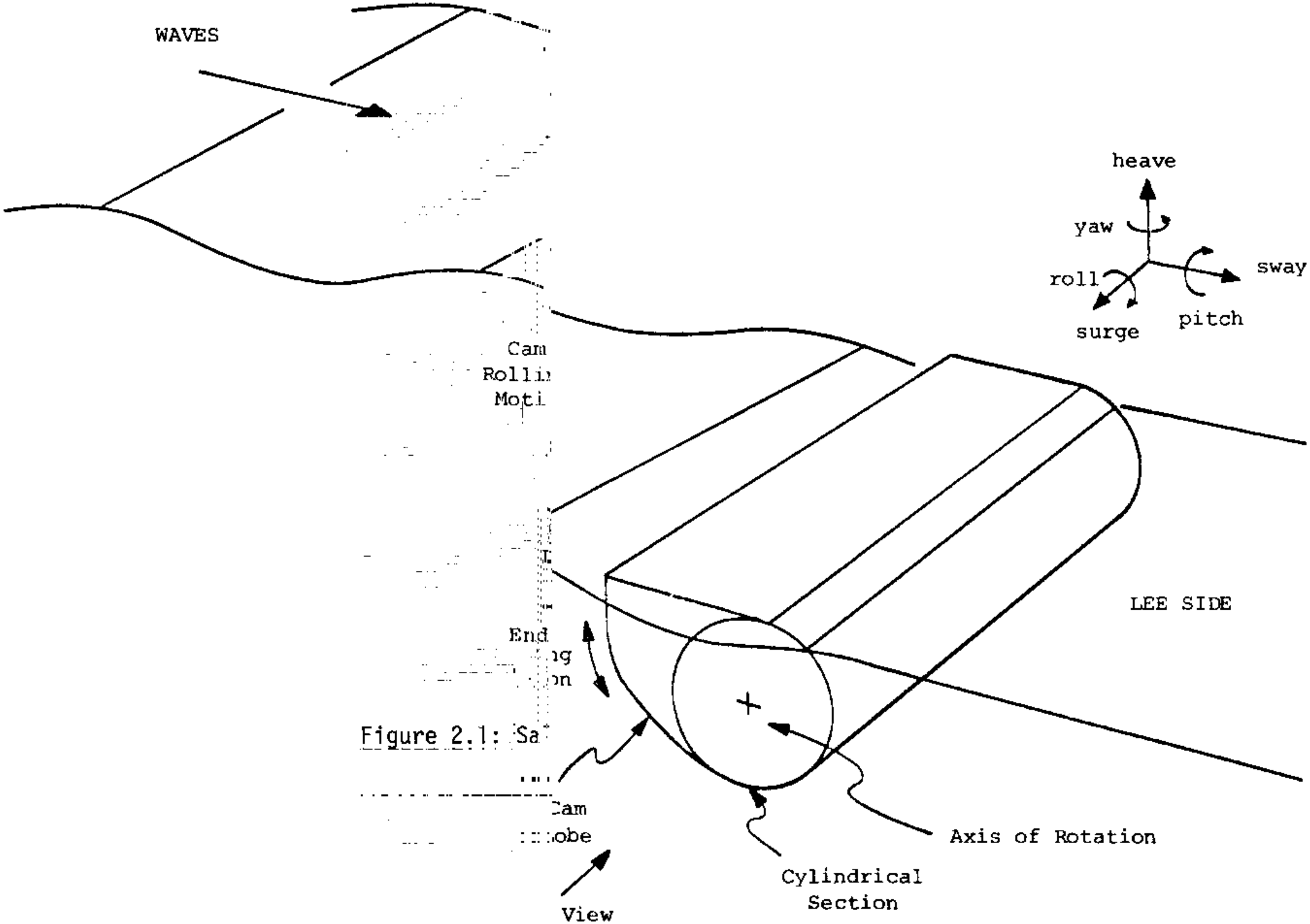

Figure 2.1: Sa[illegible] [illegible]ter Cam Wave Energy Extractor

Clearly, large amounts of power are available. If the wave energy can be extracted by the cam efficiently, and if the mechanical energy of the cam can be converted to hydraulic or electrical energy, then it may be possible to obtain significant useable energy from waves using the Salter cam. Salter's original work indicated quite high conversion efficiencies, at least for one dimensional rotary motion. Professor Douglas Carmichael of MIT undertook research to confirm the high level of efficiency of the Salter cam and to consider all of the elements required to provide a wave energy conversion system.

2.1 Comparison with Salter's experiments

The first step in Carmichael's investigation (Reference 5) was to check Salter's results by running comparable experiments on a 15" wide cam in a 15" wide wave tank. To a reasonable approximation, the Carmichael results agreed with those of Salter (see Figure 2.2, which is taken from Reference 5).

2.2 Extension of Salter's experiments

Three important extensions of Salter's experiments are reported by Carmichael. First the model cam was moved to a ship model towing tank which is 2.62 m (8' 7") wide and 39.2 m (108') long. The 15" wide model cam was used, so it was small compared to the width of the tank.

A number of interesting results were obtained. First, with the cam axis rigidly fixed, when the wave approached the cam at the normal direction (called 0° in Figure 2.3) the efficiency, based on the wave energy arriving in a 15" width, exceeded 1.0. Some form of diffraction effects were obviously feeding wave energy from sections of the wave not directly in front of the cam towards the cam. This is not surprising. Consider a reciprocity experiment - e.g., wiggle the cam and observe

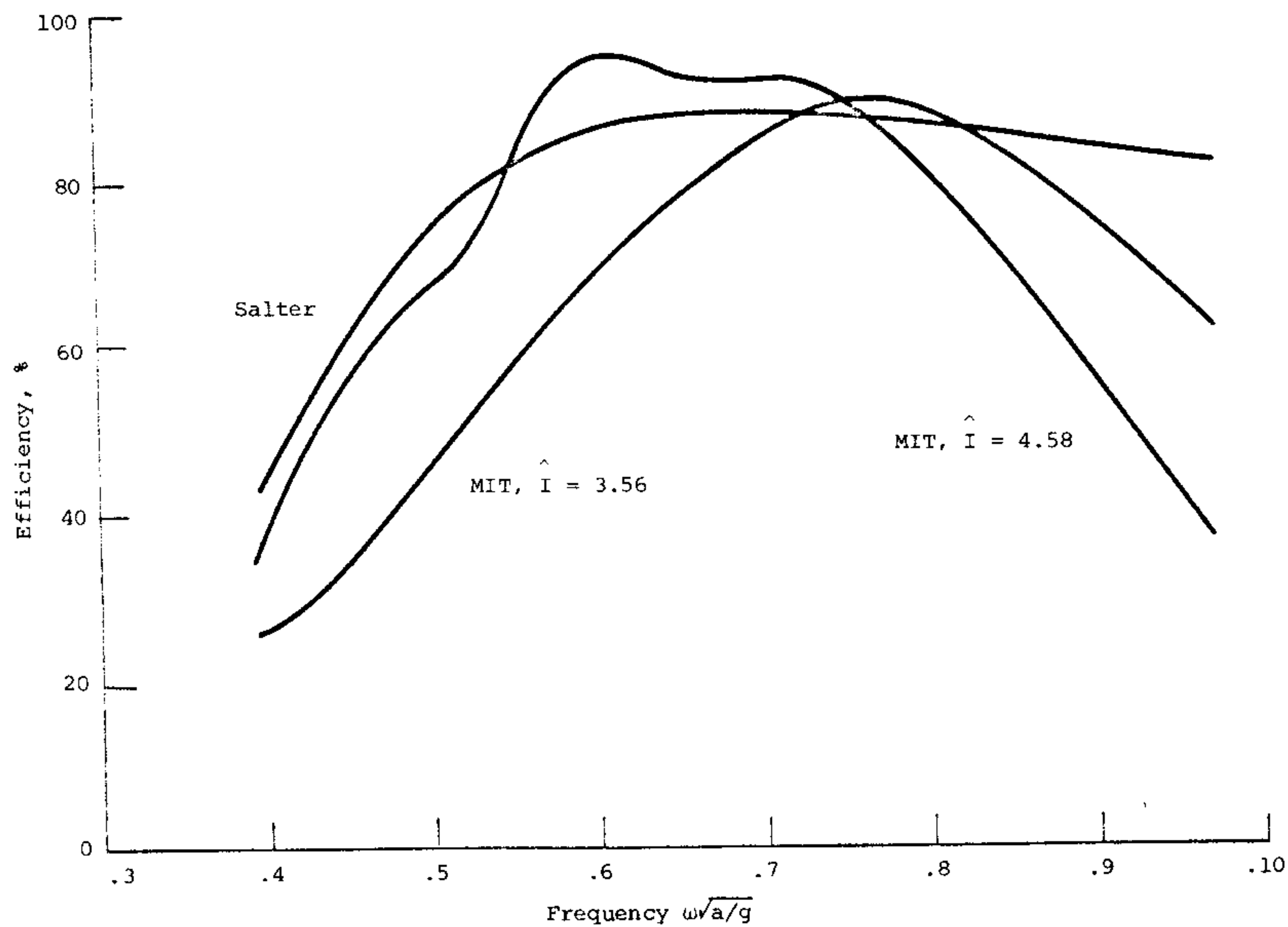

Figure 2.2: Comparison of Salter Experimental Results with Experiments at MIT, at Optimal Damping

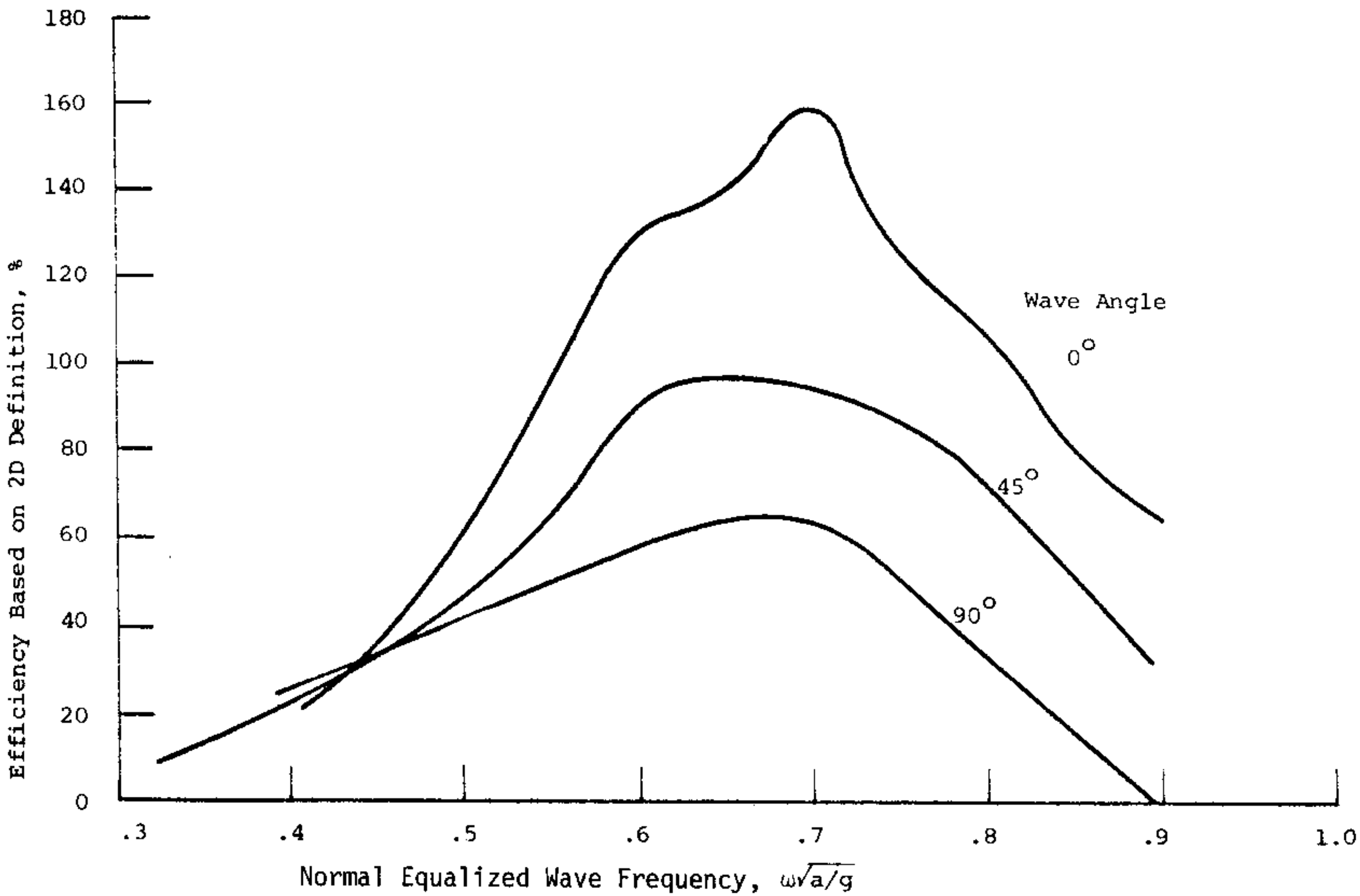

Figure 2.3: Cam Efficiency Measured at Various Wave Incidence Angles in the Large Wave Tank

the wave energy output both in a narrow tank and in a wide tank. In a narrow tank the waves will go out in one direction; obviously, in a wide tank the cam would send wave energy in all directions, not just forward. Thus the idea of its receiving energy from several directions seems also plausible. The experiment suggests that very long continuous cams may be less efficient and more expensive than short, separated ones.

A second interesting extension of Salter's work was to vary the direction of the cam with respect to the incident waves (see Figure 2.3 again). The Salter cam retains a substantial conversion efficiency even with waves traveling parallel to the rotational axis of the fixed cam. This is a result of the asymmetrical cross section of the cam which causes the cam to rotate as the waves rise and fall, provided that wave length is long compared to the width of the cam. At wavelengths commensurate with the length of the cam it was observed that the cam efficiency was low. It thus appears that the cam performance when placed perpendicular to the wave crests can be explained qualitatively in terms of the quasi-static buoyancy forces.

The third extension of Salter's experiment was to investigate moorings and attendant mooring forces which would be required to maintain the efficiency of the cam. It was found that slack moorings could not be used. The cam would heave and roll and yaw and pitch rather than simply roll on the proper axis. Various attempts were made at stabilizing that cam by adding mass to its frame and providing damping. For the model at least, a taut line (tension) mooring seemed to be the best solution. A number of moorings were tested to prevent random motions of the cam and to constrain the axis of rotation so a torque could be devel-

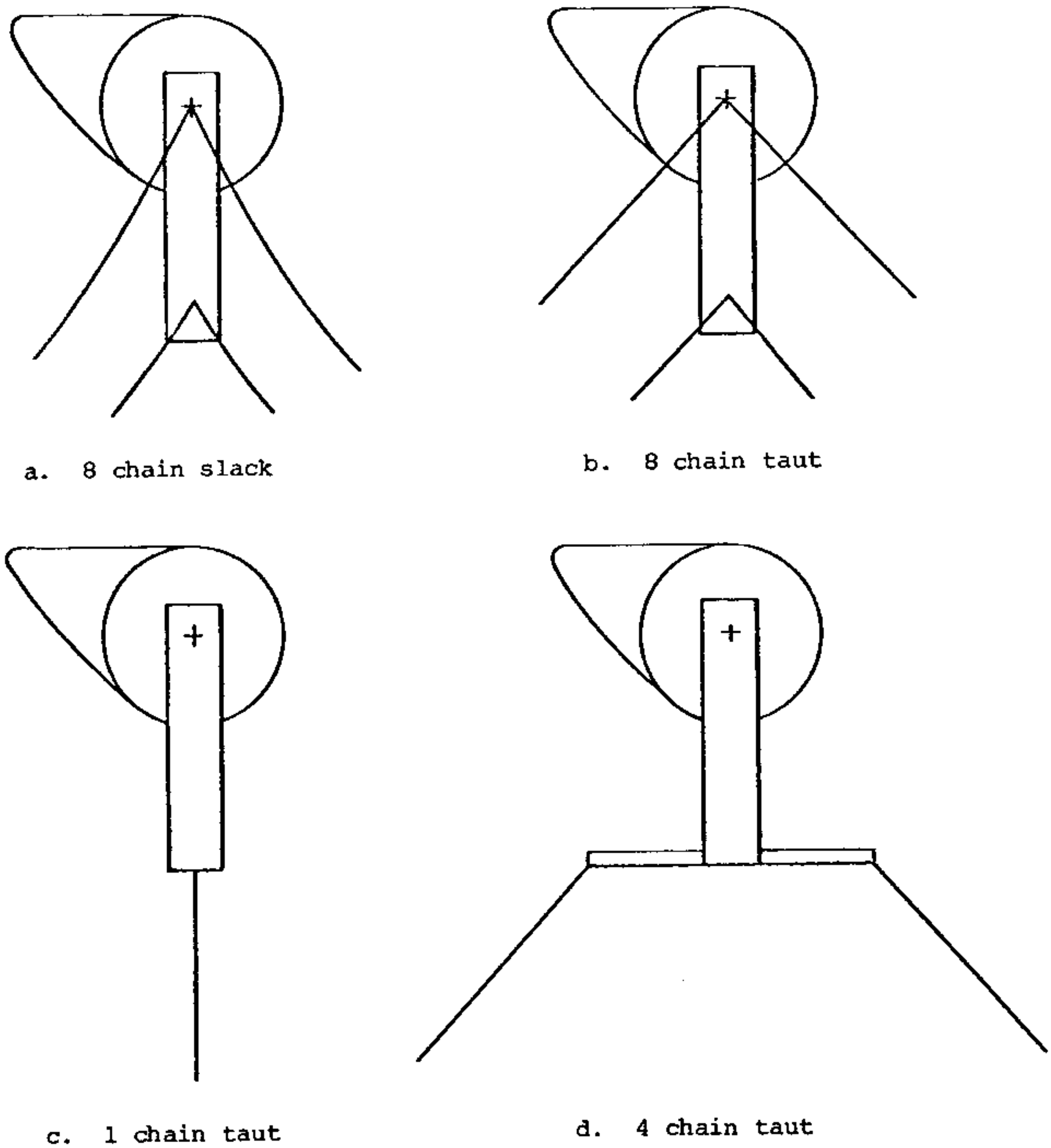

Figure 2.4: Arrangements of Moorings Tested in the Towing Tank

opea. These are shown in Figure 2.4. The most satisfactory results were obtained with a taut mooring system with 4 lines.

Work by Myneth et al provides a theoretical confirmation for some of the mooring experiments carried out by Carmichael (see Reference 8).

2.3 Engineering evaluation of approximate costs of two Salter cam systems

Professor Carmichael chose to consider a single small cam system with an internal energy conversion device, a suitable mooring system, and an electrical cable to shore, rather than the several kilometer long units proposed by Salter. A taut mooring system similar to that investigated experimentally was assumed (see Figure 2.5).

Power output and costs were evaluated for cams located at two New England sites. One was assumed to be three kilometers off Nauset Beach, Cape Cod, Massachusetts. Another site was assumed to be 200 kilometers off the Massachusetts coast. Historical average wave spectra data for each site were used to obtain average wave power outputs and average conversion efficiency. The units were made in lengths consistent with expected stresses and standard naval architecture practices were used to obtain design parameters. Steel costs and mooring costs were calculated from the expected displacements. The costs of electric transmission were assumed to be $40,000 per kilometer, independent of the power carried by the cable. The underlying assumption is that the cost of laying the cable is the dominant cost and that cable laying costs are not very dependent on cable size. The dimensions and costs are shown in Table 2.2 below.

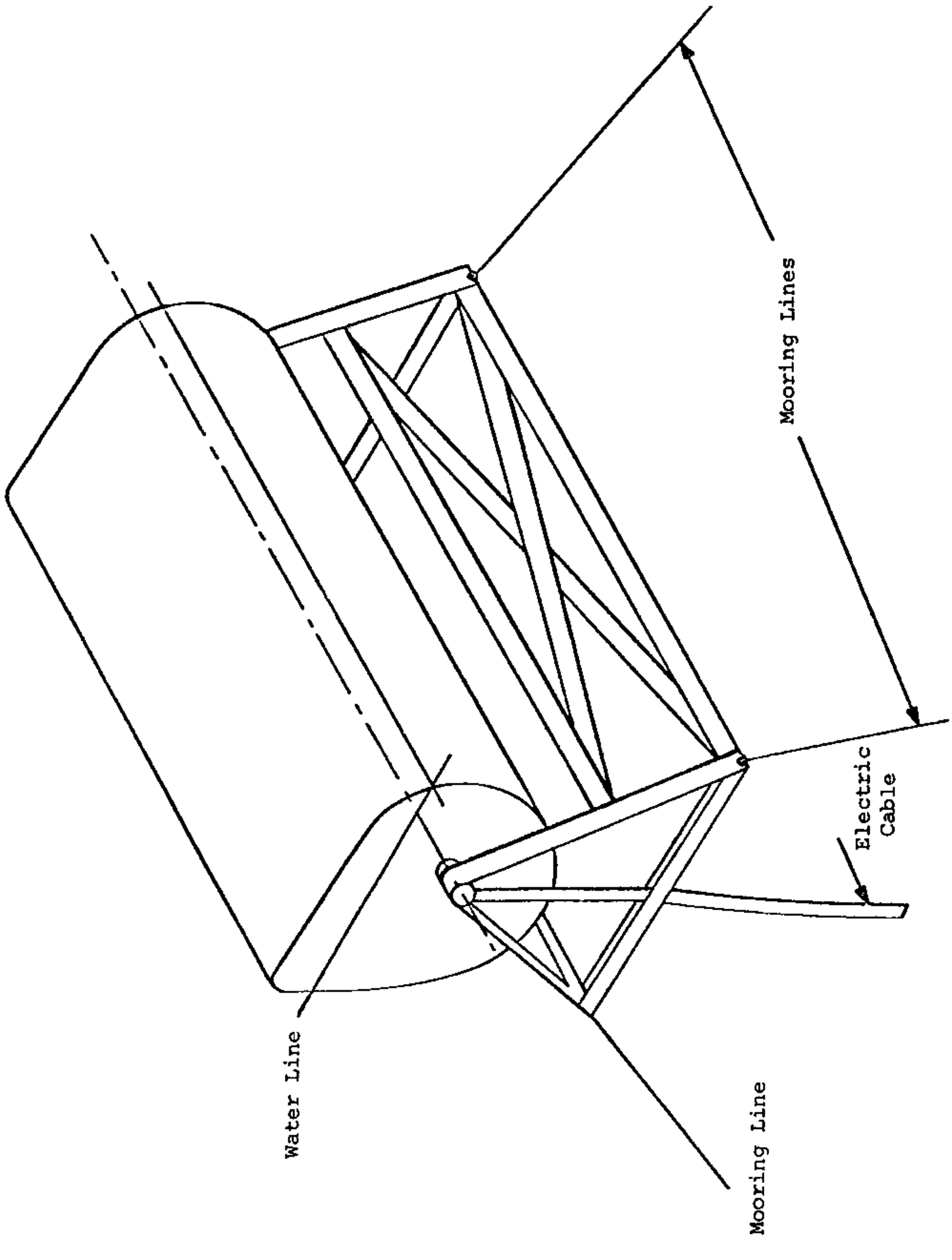

Figure 2.5: Possible Arrangement of a Moored Cam

Table 2.2

Predicted Capital Costs for Two Representative Systems

	Cam Dimension Radius	Cam Dimension Length	Average Power (Kilowatts)	Total Cost	Cost/Kilowatt
Nauset Beach	7.6m	85m	282	$3,657,000	$12,967
Ocean Site	4.8m	69m	1,143	$12,190,000	$10,667

Note that the near shore device is very much larger for two reasons. First, the average available wave energy near shore is lower, and second, because the period is low and the wave lengths are long, the radius is large. Thus, in terms of size, the near shore device is very much less efficient. The breakdown of costs is revealing in this regard and is given in Table 2.3 below.

Table 2.3

Approximate Cost Breakdown for Cam Systems

	Nauset Beach Cam	Ocean Site Cam
Fabricated Steel Cost	23%	5%
Mooring Cost	62%	12%
Electrical Generator System	4%	16%
Transmission Cable	11%	67%

For the near shore device, the mooring costs are almost 2/3 of the total cost, and the structural costs are almost 1/4 of the total cost. For near shore devices, it is clear that lower mooring costs are essential for an economically competitive system. This suggests that near shore, at least, the Cockerell rafts described in the following section which have simpler structures and much lower mooring force are much more promising.

For the ocean site system, the cam is much more efficient on a size basis. Because available wave power is higher and because wave periods are higher and wavelengths are shorter, we obtain more power per dollar at the site even with the relatively large mooring costs, which are still almost $2\frac{1}{2}$ times greater than the cost of the fabricated steel for the cam. The cost breakdown, however, reflects a basic unsolved problem of all wave energy devices. Namely, one must move away from the coast to get high power density in waves and hence efficient mechanical wave energy converters. However, the cost of getting the power ashore remains a formidable hindrance. It was assumed that the cost of the cable in place was about $40,000 per kilometer - <u>independent of the power carried</u> - or about $8,000,000. On this assumption (i.e., that the cost of cable in place is, to a first approximation, independent of power carried), the unit cost of 5 cams, 200 mile off the coastline, was calculated to be only $4,300/kw.

In summary, Salter cams appear to be efficient converters of wave energy to mechanical energy. However, mooring costs are much larger than the structural cost. If a different way can be found to support the torque in roll and to prevent heave and pitching, then the mechanical system could be reduced in price by a factor of two or three. However, costs of carrying power long distances underwater suggest near shore systems with relatively low power may be more attractive.

3.0 The Hagen-Cockerell Raft System

3.1 General

The Hagen-Cockerell Raft (Ref. 2, Ref. 3) in a simple form can be described as a string of floating hinged rafts (See Figure 3.1). Wave energy is transferred to the raft as waves travel under the rafts, and power can be extracted by pumps or other energy converters actuated by the angular displacement between adjacent rafts. While conceptually simple, these rafts present a formidable analytic problem. The number of rafts can be a variable, for example, and the length of each raft in the string of rafts may be different. Intuitively one might guess that for a given wave length there is a single optimum length for a pair of rafts, and for a wave spectrum with two peaks, there may be an appropriate set of lengths of three or more rafts to match the two peaks. Such optimization suggests that conversion efficiencies could be made quite high over the wide spectrum of wavelength one sees in the ocean.

In concept, it appears that drag (and hence, mooring) forces on the Cockerell rafts are much less than for a comparable Salter cam for several reasons. First, the Cockerell raft is a surface device and might have a thickness or depth of about one meter versus 10 meters for a Salter cam. Therefore, the wave forces should be much lower on the raft. Second, a raft has no need for a fixed axis of rotation and hence no need for a "taut" mooring. The mooring can be relatively slack. Third, since a chain of rafts might extend over a typical ocean wave length, forward forces on one raft may tend to cancel backward forces on another, so that the net forces on the mooring originating from wave

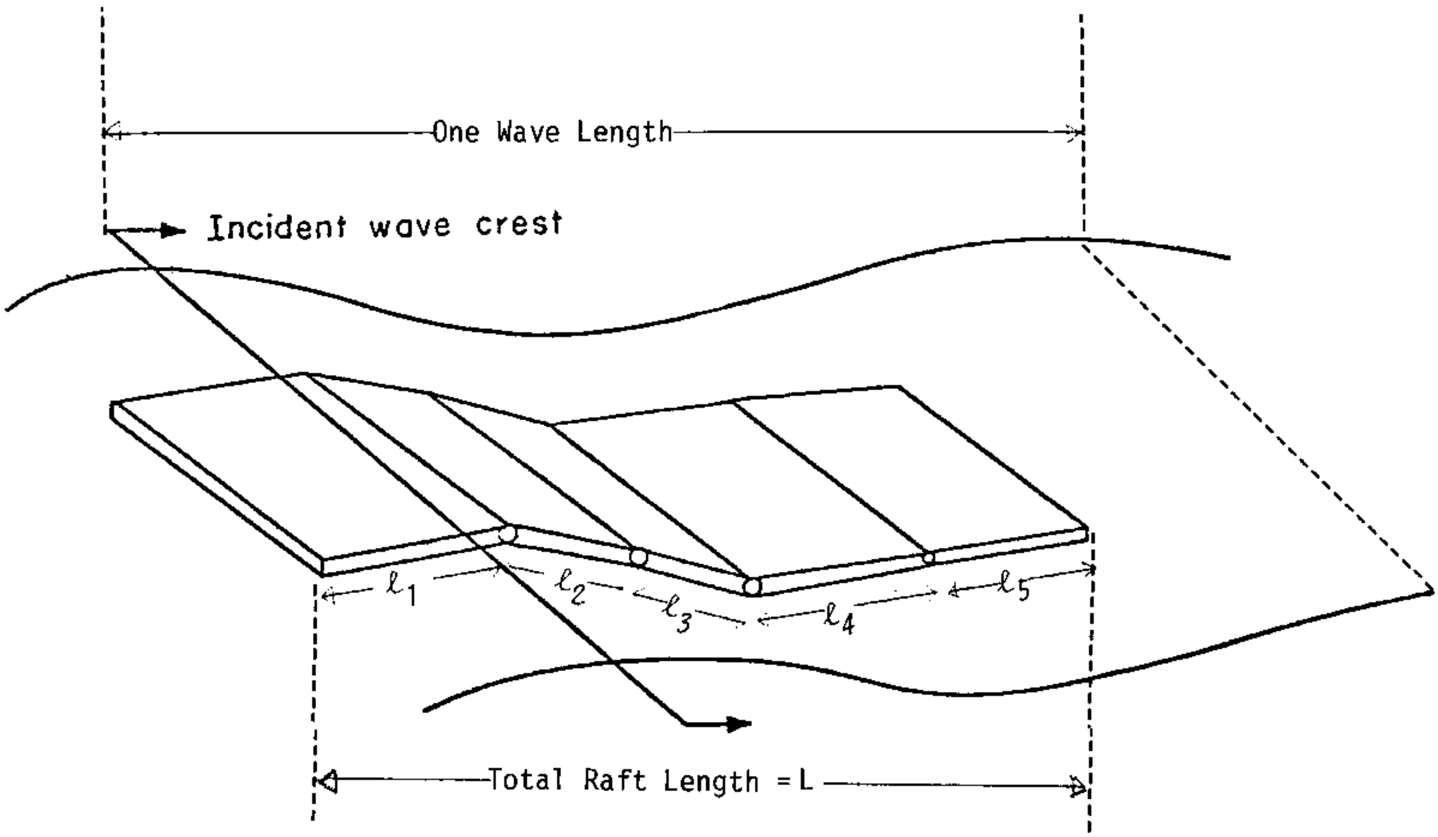

FIGURE 3.1 A Hagen-Cockerell Raft Chain

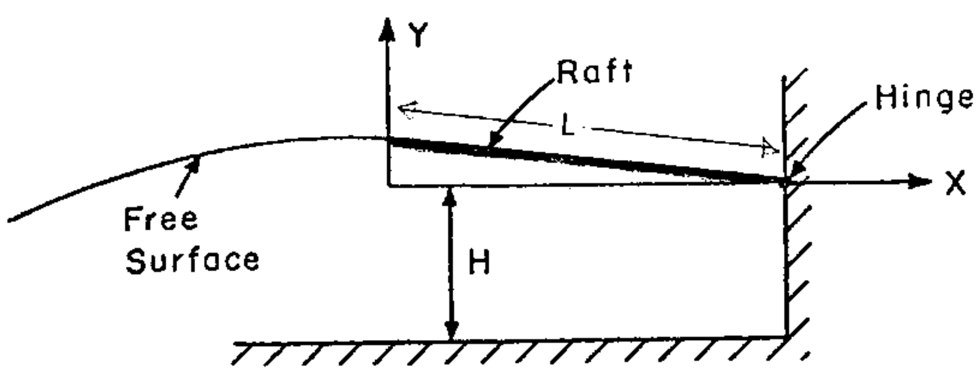

FIGURE 3.2 The Coordinates for Analysis of the Hinged Raft System

action on the train of rafts may be quite small.

Because of these potential advantages, Professor Mei and a doctoral student, Pierre Haren (Reference 4), have investigated such devices analytically. The results are highlighted below.

3.2 A single raft hinged on a wall

Haren derives the efficiency of a single raft hinged against a wall as shown in Figure 3.2. Subject to such usual assumptions as small displacements, a two dimensional solution (an infinitely wide raft), and only normal incident waves, he derives the efficiency of the raft (extracted wave energy/incident wave energy) as a function of the ratio of raft length to the wavelength of approaching waves. Some representative results are shown in Figure 3.3 in which k is 2πx total raft length/wavelength and alpha is a non-dimensional geometrical parameter depending only on water depth and raft length. One finds that

1) for a given wavelength, the efficiency can be 100% at a single wavelength, if alpha is properly chosen, e.g. 0.125;

2) one can "trade" between the maximum efficiency at one value of k and the bandwidth of efficiency over a range of k by increasing alpha;

3) the peak absorption occurs when the ratio of the raft length to wavelength is about 0.4 (e.g. k = 4.0 = 2πL/wavelength for all alphas.

These results are qualitatively similar to those for a Salter cam, and lead to investigation of more complex systems, such as that shown in Figure 3.1.

3.3 Multi-raft Chain

The analysis of the rafts was done in a very general manner

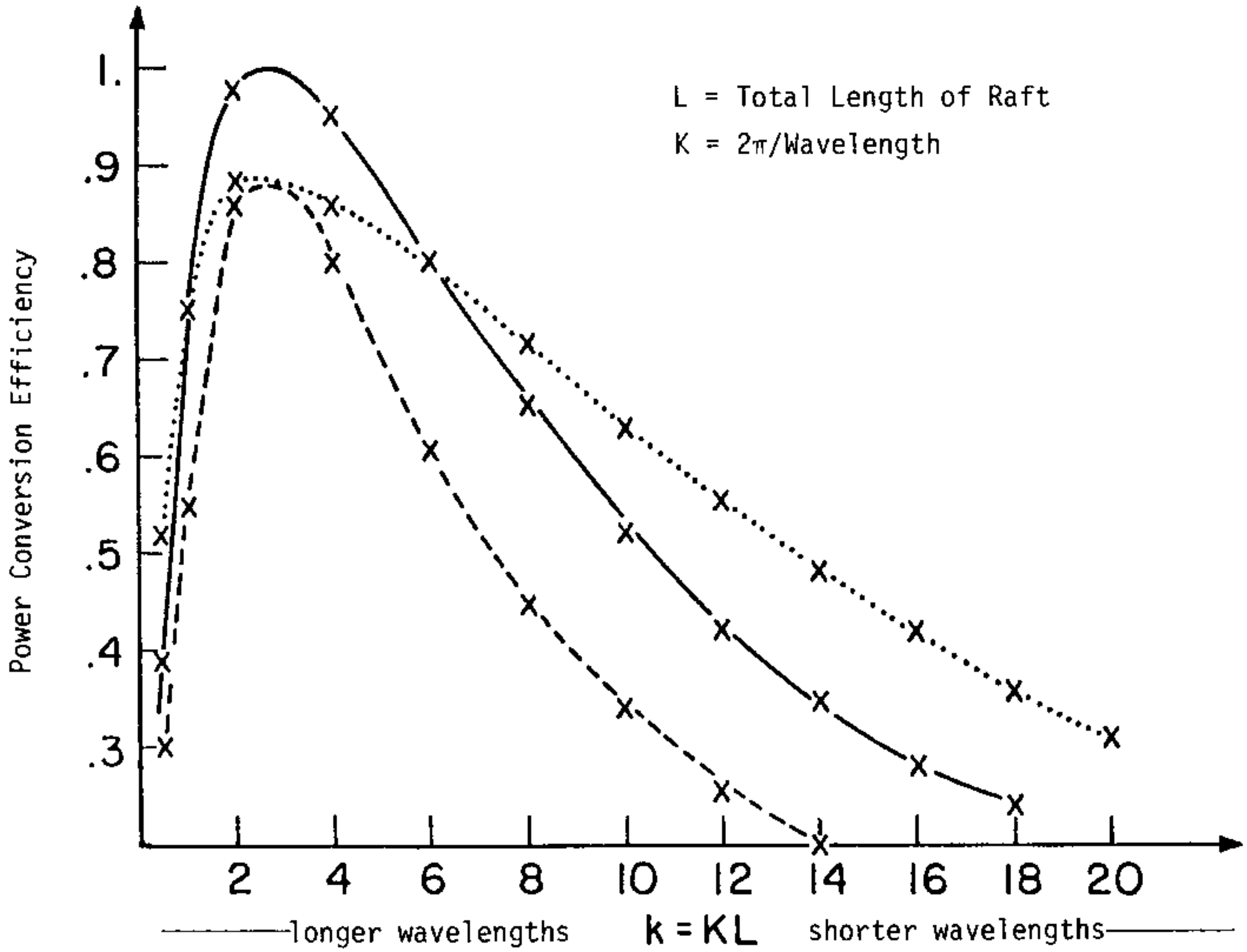

Figure 3.3: Power Conversion Efficiency for a Typical Hinged Raft

—x— $\alpha = 0.25$; - - - x - - - $\alpha = 0.125$; ····x···· $\alpha = 0.5$

and representative systems were analyzed changing one variable at a time to illustrate the effect on efficiency of various dimensions, number of rafts connected, etc. Various optimizations were carried out subject to various constraints including economic ones. Clearly the number of permutations and combinations of variables and constraints is large. We will give only representative, significant results here.

3.3.1 Optimization for a single wave length with an assumed total raft length yields an efficiency curve such as that shown in Figure 3.4. For this example the single wavelength was chosen at 171 feet and the period was 5.5 seconds. For a train of 3 rafts the optimum lengths are 54.0 feet, 171.2 feet, and 224.0 feet long. There was no gain in efficiency by considering trains of 4 or 5 rafts.

3.3.2 Optimization for a single wavelength with a cost constraint (i.e., optimizing a measure of efficiency minus cost) yields a quite different result (see Figure 3.5). The cost function introduces the economic reality that as the rafts get longer, more capital is needed to build them. Subject to this constraint, it appears that an optimum train is formed by two short rafts (each about 50 feet long) hinged at the two ends of a center raft (about 116 feet long). The total length is only 214 feet. The peak efficiency is reduced to 81% and a more substantial fraction of the energy is absorbed at the second hinge. When a fourth raft was added, the economic constraints forced it to a negligible size.

3.3.3 Optimization for other sea spectra yielded comparable results for a representative double peaked spectrum representing an average over a year of a real spectrum of wavelength obtained from the North Sea.

Note by comparing Figures 3.6 and 3.7 that the optimization

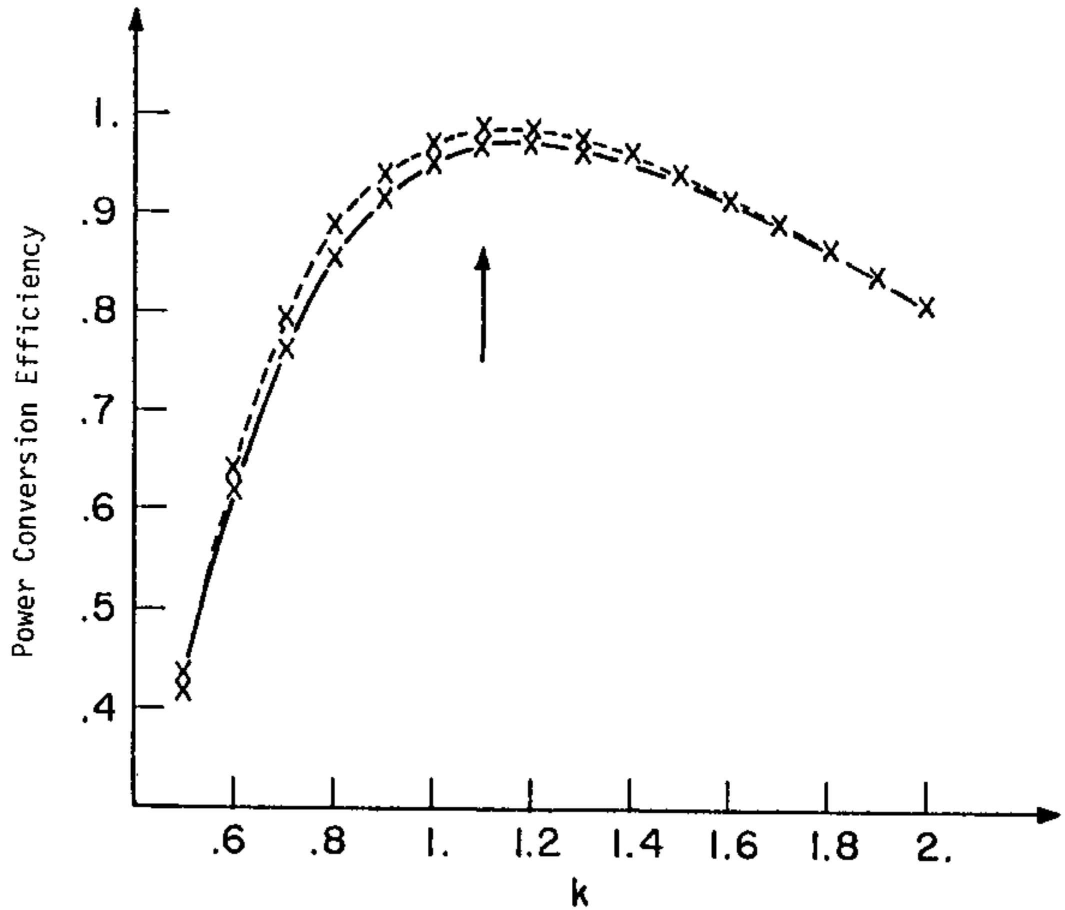

Figure 3.4: Optimization for a Single Wavelength With an Assumed Fixed Length

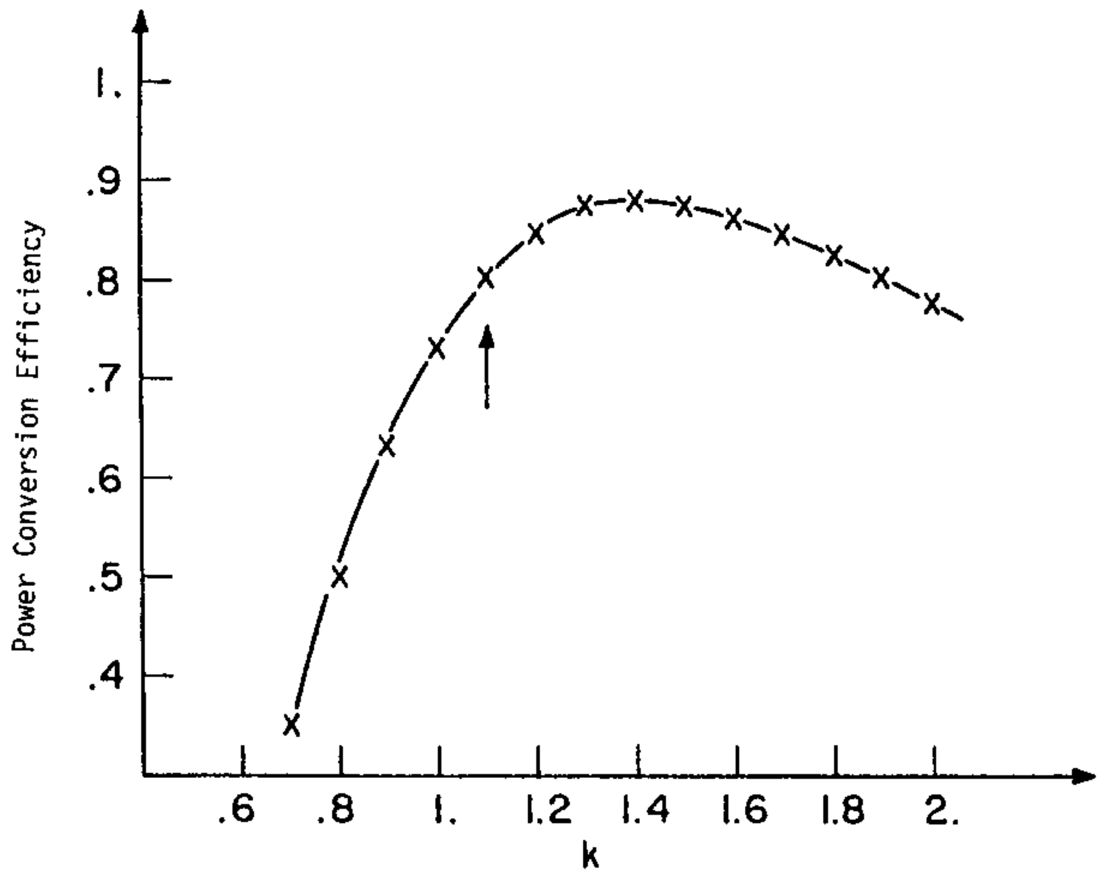

Figure 3.5: Optimization for a Single Wavelength With a Cost Constraint

for this wave spectrum subject to cost constraints produced a radically different efficiency curve from that which is not optimized with respect to cost. When the cost of the length of the rafts is included, the shape of the curve shifts away from the long waves toward the short waves. Thus it appears uneconomical to try to capture the energy in the long ($k < 1$) wavelengths of the spectrum.

3.4 Summary of Cockerell Raft Design

Analysis and optimization studies of Haren and Mei suggest the Cockerell raft has some theoretical and practical advantages over the Salter cam. In general the efficiency curves are broader, the rafts are less complex to build and to moor, and should be much cheaper than Salter Cams. Note, however, that the angular displacements between the rafts are very small, a few degrees, and devices for using these small displacements to generate power are not yet designed. It would be of value to use Carmichael's cost figures and data on a raft design for a better cost comparison of the Cockerell rafts and Salter cams.

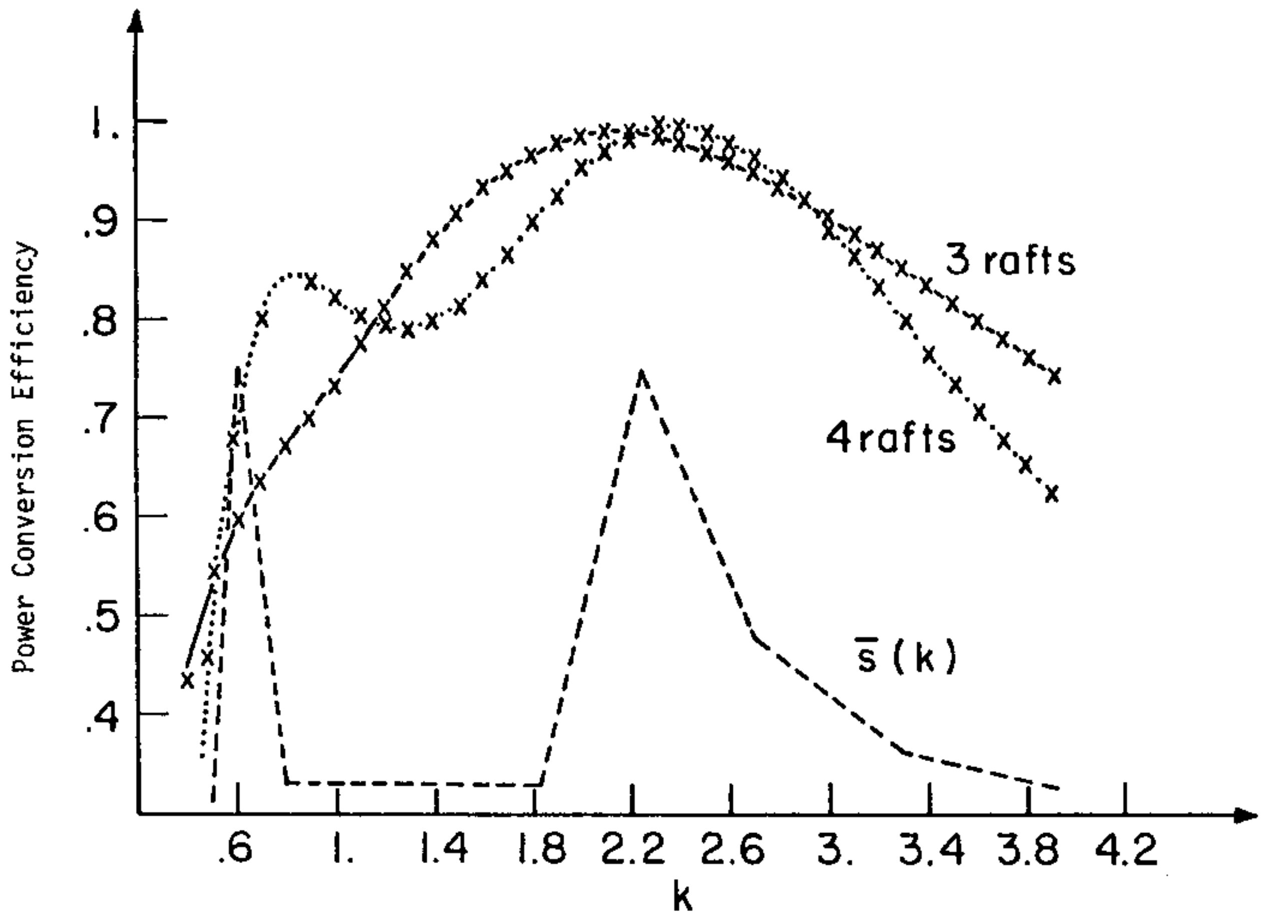

Figure 3.6: Double Peaked Spectrum. Optimizations for Fixed Total Length

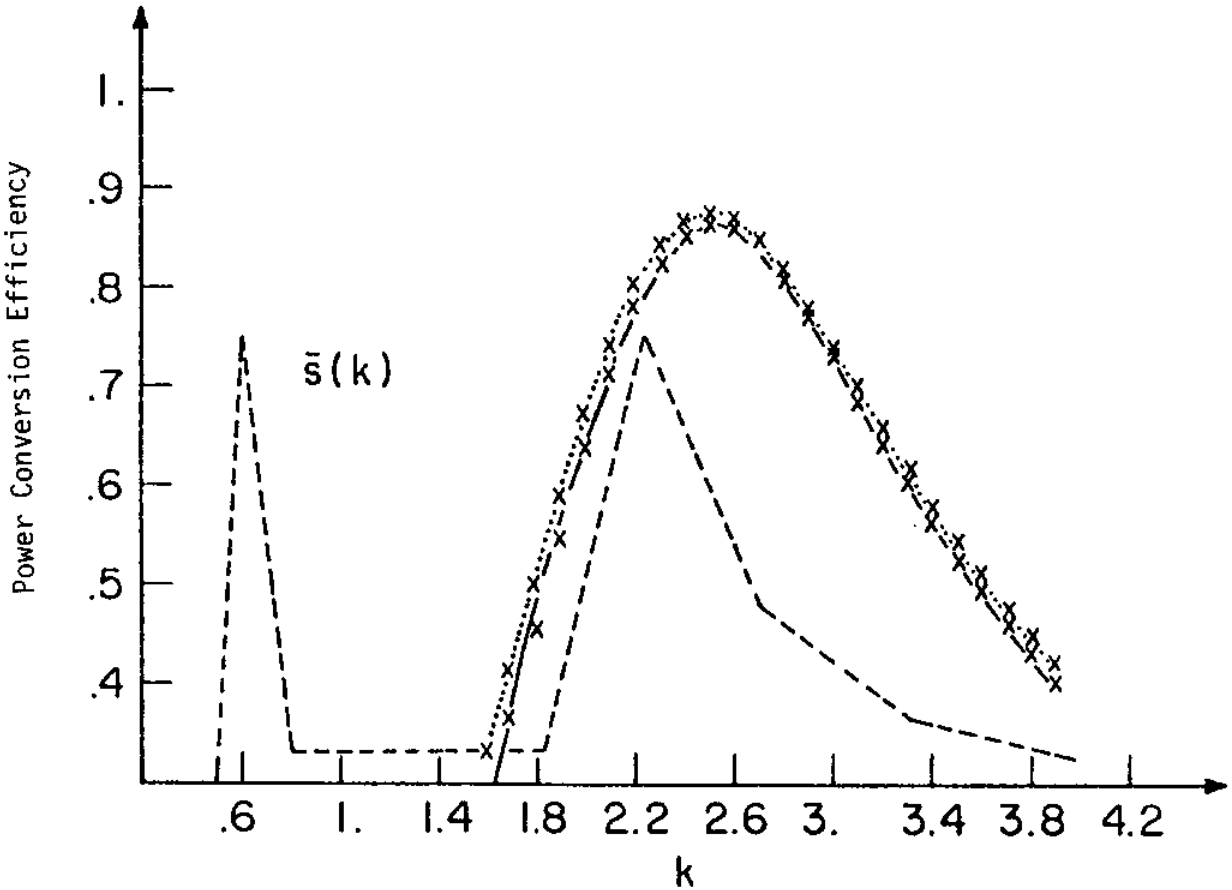

Figure 3.7: Double Peaked Spectrum. Cost Optimization for 3 and 4 Rafts

——— x ——— 3 rafts; ········ x ········ 4 rafts.

4.0 A Wave Power Application

4.1 General

Dr. Michael Pleass of the University of Delaware (Reference 6) has taken a market approach to utilization of wave power. Noting the ample evidence that cams or rafts can convert wave energy to mechanical energy efficiently, he observes that the costly and difficult problems arise from trying to convert to hydraulic energy and/or to electrical energy and then getting large amounts of electrical power to shore over very large distances. He suggests an important application that may minimize these crucial problems since it does not involve large (thousands of megawatts) amounts of power or great transmission distances.

Dr. Pleass' prime interest is in the critical need in underdeveloped (and in some developed) countries for fresh water for farming. He views the process of reverse osmosis as a promising means of converting salt water to fresh water. A key problem in reverse osmosis technology is the need to pump large quantities of water through a membrane at high pressures – on the order of 50 atmospheres. At these pressures fresh water output is obtained at a rate of about 5,000 cubic meters per day for each megawatt of power, or roughly one gallon per day for each watt of power.

As noted in Table 2.1 above, available wave power off U.S. coasts is on the order of 2 to 6 megawatts/kilometer. In the U.S. Virgin Islands 3 megawatts/kilometer is typical and in areas like the East Coast of Somalia 20 megawatts/kilometer can be expected.

Allowing for 25% to 50% efficiency in converting from available wave power to hydraulic power one obtains the approximate result that one kilometer of wave conversion devices could yield a million gallons of fresh water per day.

According to Dr. Pleass, a 1 megawatt wave energy extractor would be competitive with diesel electric power for remote areas if the cost were held to between $3.0 and $4.6 million dollars - more importantly, the desalination systems would not be dependent on oil supply.

4.2 High pressure pumps for use with wave energy extractors

The basic engineering problem for a high-pressure sea water pump is to obtain a long lifetime with almost no maintenance, which implies very low wear and an insensitivity to trace elements in sea water. Two versions of such a pump are being developed at the University of Delaware and are shown in Figure 4.1 and 4.2 respectively. Professor Pleass discusses these pumps and the economics in more detail in Reference 6.

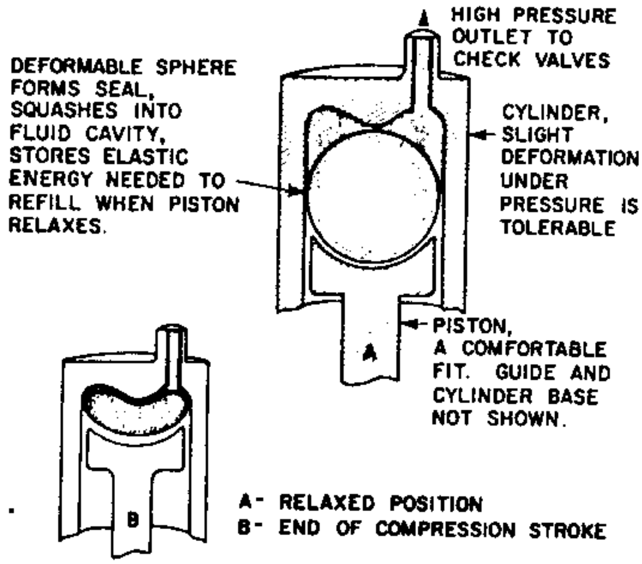

Figure 4.1: Short stroke version of the elastomeric sphere pump

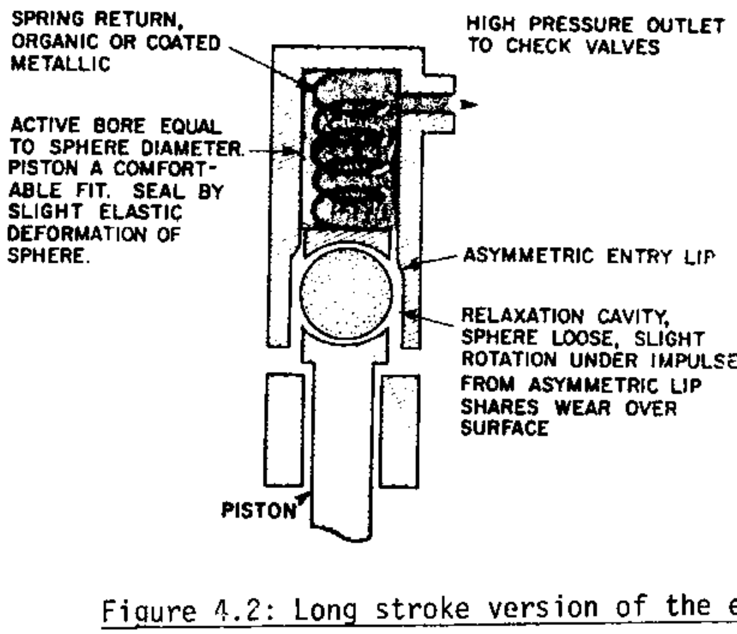

Figure 4.2: Long stroke version of the elastomeric sphere pump

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