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SOLAR SEA POWER PLANTS (SSPP)

A Critical Review and Survey

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A Critical Review and Survey

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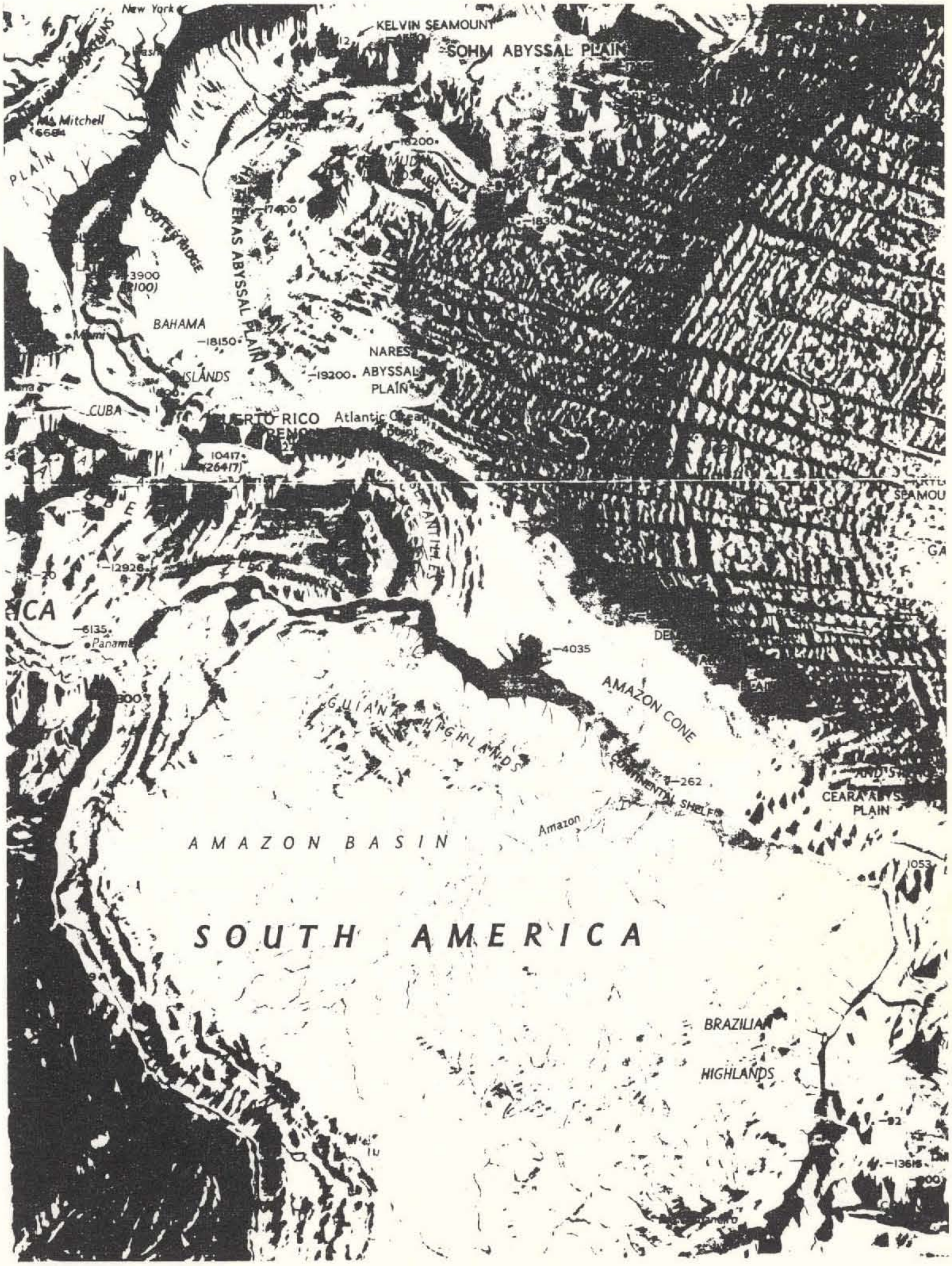

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SOLAR SEA POWER PLANTS (SSPP)

A Critical Review and Survey

I. INTRODUCTION

This report is a critical survey of the SSPP concepts considered relevant and important to the eventual success or failure of the SSPP itself. It is a result of a 10 week study of the SSPP. As a consequence of the amount of time spent on this survey, there will be gaps in the literature quoted and certain concepts that are not gone into in the detail that is commensurate with their importance. The author is solely responsible for the content of this report and any inaccuracies are probably due to him. Also, all recommendations are his alone and were evolved after some periods of short but intensive thought.

In a manner of speaking this entire report is an extended introduction to the SSPP itself, its economics, alternatives, problems and contradictions.

The author would like to acknowledge his gratitude to those who have assisted him in the preparation of this report. Special thanks are due to Tom Golden for getting the author interested in the SSPP project and for having a certain degree of confidence in him. The author thanks Bill Cherry for being his colleague and acknowledges the fact that without the long and detailed discussions he had with Jack Peake this report would not have attained its final form. The author would also like to thank the rest of Code 704; Elaine Bobbitt for explaining some intricacies of the system. Special thanks go to Dr. Robert Cohen of the National Science Foundation who the author relied on as the SSPP expert and through whom the author was put in contact with various SSPP researchers.

Finally, this report relates to the present state-of-the-art and the building of demonstration plants and not to the eventual massive build up of ocean-based SSPPs. It is crucial that any demonstration projects be very successful if the SSPP concept is to grow and eventually succeed in producing significant amounts of energy, and it is to the demonstration aspects of SSPP design that this report addresses itself.

II. THE ENERGY PROBLEM

The problems associated with both the availability of adequate supplies of energy, to meet the needs of the individual and industry, and the unavailability of adequate energy resources to meet demand have been adequately and incessantly voiced in the technical literature, popular magazines and daily newspapers. It therefore appears to be sufficient to review only a few general ideas that may have direct bearing on Solar Sea Power Plant (SSPP) concepts.

In view of the changes in attitude that have taken place due to the energy shortage and the consequential price increases for energy, most of the predictions made concerning future energy use, both in type and magnitude, will have to be revised. This is especially true of the all too common exponential growth curves and the equally inaccurate linear extrapolation models. It appears clear that we will be using more energy by the year 2000. However, the sources of that energy (coal, solar, wind, oil, geothermal, nuclear, hydroelectric, etc.) cannot be predicted with any assurance beyond a 20 year interval.

One consequence of this is that without the long range integrated planning of the total energy resource and use system the American people will experience a serious deterioration in the quality of their environment. This will be most serious in two areas:

(a) The east coast urbanized area which extends in almost a straight line from the start of this megalopolis north of Boston to its termination south of Washington, D.C. This area includes the cities of Baltimore, Philadelphia, New York, Providence, Hartford, Newark, Wilmington, etc.

(b) The second area is the Great Lakes region and includes those cities bordering on the Great Lakes such as Buffalo, Cleveland, Toledo, Detroit, Chicago, Milwaukee, etc.

There are other populous regions with problems such as Southern California, the Gulf Coast, the Ohio Valley and the Mississippi, but the most serious problems will arise in the former two areas.

In any case all the areas mentioned are likely to have significant population increases over the coming decades and it is likely that their urbanized areas will increase significantly. In addition, more large electric power generating facilities, heavy industry and manufacturing sites will likely be constructed in and around these population concentrations. One must also consider that the number of road vehicles will increase in proportion to the population and the various automobile and truck problems will be magnified in time.[1]

According to the best estimates available, the pollution problems in our urban areas will not be solved before the year 1995. With respect to crude oil it is reasonable to expect the earth's supply will be essentially depleted in approximately 100 years due mainly to the growth in the world's yearly energy consumption.[2] Figures 1 and 2 (from Ref. 2) graphically illustrate the overall tendency of greatly increasing worldwide energy consumption. These curves are likely to be accurate because of the steady industrialization of previously underdeveloped nations.

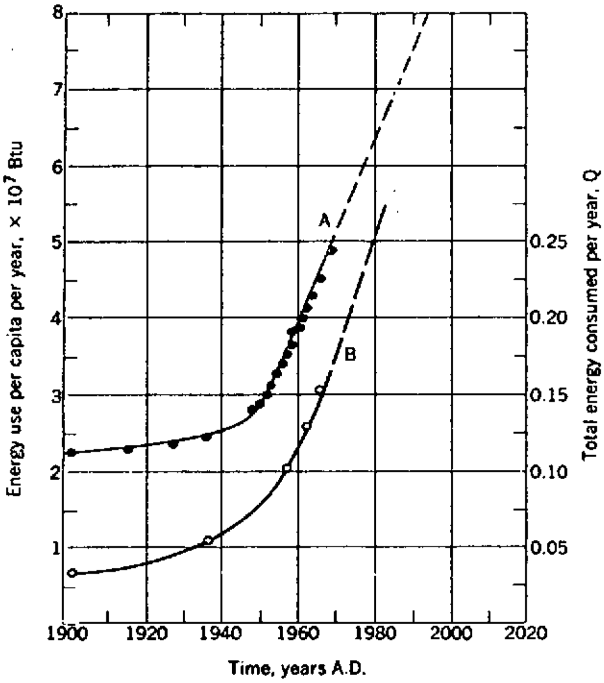

Figure 1. World Energy Consumption Since 1960. Curve A measures the energy use per capita per year; Curve B, the total energy consumed per year.

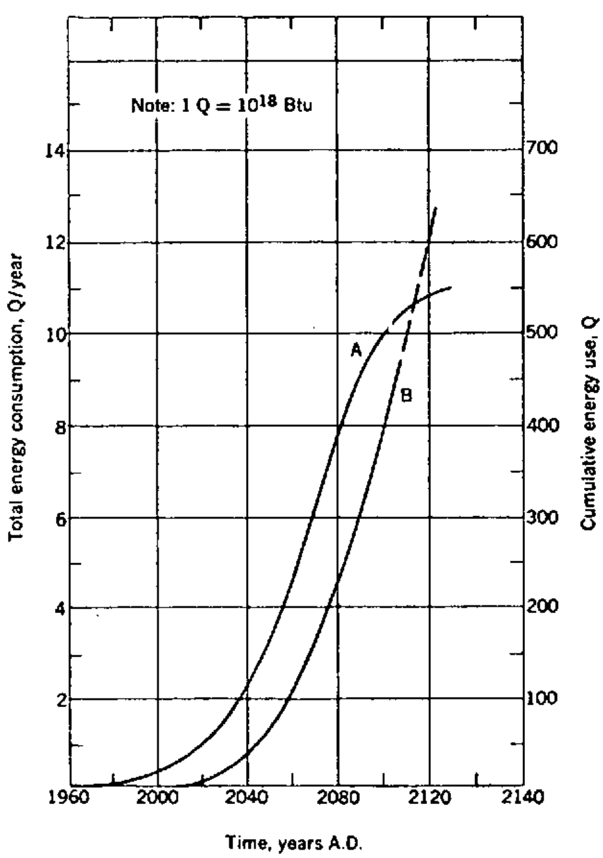

Figure 2. World Energy Needs Since 1960. Curve A measures total energy consumption, and Curve B indicates the cumulative energy use.

From the data indicating ever increasing numbers for the earth's fossil fuel reserves, we will doubtless still be dependent on fossil fuels for the major portion of our electric power in the year 2000 and for some time thereafter. Therefore we will have to contend with both thermal and chemical pollution until that time. By the year 2000 the U.S. may well be environmentally cleaner, but the world will be a much dirtier place (see Figures 1 and 2). For example, a 3,000 MW oil burning power plant, using crude oil with a 3% sulfur content, will produce daily: 700 tons of sulfur oxides, 180 tons of nitrogen oxides, 6 tons of soot and other particulates and 5.4 tons of various hydrocarbons. And now with increasing prices for oil the power industry's claim that pollution control devices are uneconomical take on noteworthy environmental importance. The average citizen is for the most part unwilling to pay for pollution control in addition to the present relatively high energy prices. Also, pollution control devices can use up to 10% of the power being produced by a power plant. This is not only uneconomical, but adds to existing power shortages, Also, no pollution control device is 100% effective and even with massive multibillion dollar efforts there will always be a pollution problem in heavily populated areas.

The thermal pollution problem is also serious. A typical large electric power plant will reject 60% or more of its total heat to the environment. Thus if 3,000 MW_{elect} are produced in a fossil fuel power plant, about 4,500 $MW_{thermal}$ will be rejected to the environment, i.e., 3,800 $MW_{thermal}$ via the cooling fluid and 700 $MW_{thermal}$ via the chimney gases. Thermal pollution problems are not well understood at this time; especially the environmental effects over long periods of time.

These facts alone (aside from political and other consideration) would warrant a closer look at the SSPP. But first let us consider another alternative; nuclear power. There are now approximately 290 nuclear power reactors operating in approximately 25 nations. By the year 2000 the equivalent of one new 1,000 MW_{elect} nuclear plant will be brought into action each day.[3] One great advantage of a nuclear power plant is that it will not produce any chemical or particulate pollutants. However, thermal pollution poses a greater problem in nuclear power plants. If our 3,000 MW_{elect} fossil fuel plant was a nuclear power plant it would reject 5,600 $MW_{thermal}$ to its cooling fluid, or about 50% more than the fossil fueled plant. This is not the only problem, however. Nuclear power plants will in the long run emit small amounts of long lifetime radioactive material. As power production expands the background radiation levels will gradually rise in the power plant's vicinity. Krypton-85, radon and tritium gases are normally produced in the course of the normal reactor cycle. Other isotopes are either stored or released into the cooling fluid (lake or ocean) at low concentration where they may be concentrated in food chains.

The only thing that need be said about the radioactive waste disposal problem is that a final solution has not, as of yet, been proposed. Disposal remains a very serious problem that must be solved before we become significantly dependent upon nuclear power.

The greatest drawback, real and psychological, possessed by nuclear power is its catastrophic potential. After the fuel elements of a 1,000 MW_{elect} power plant have been in operation for one year the fissionable material produced in the sheathing of the fuel elements is equivalent to that produced by a 50 megaton fission bomb.[4] Thus an accident rupturing the fuel sheaths could send millions of curies of harmful radiation into the local environment.

An even greater potential problem is the possibility of a loss-of-coolant catastrophe.[5] Without getting into details, this would scatter massive amounts of radioactive material into the atmosphere which could be lethal for dozens and under some conditions up to 100 miles. If this occurred in any of our great population centers such as the east coast or Great Lakes regions millions could perish.

With all this in mind let us consider an attractive alternative to producing power: the SSPP. While the SSPP will not be the answer to the nation's energy problems, it may nontheless play an important role in reducing these problems. Ocean thermal energy is an inexhaustible resource for as long as the sun shines and offers the possibility (as will be described below) of providing food (mariculture) and fresh water (desalination) as byproducts.

III. THE SOLAR SEA POWER PLANT (SSPP): AN OVERVIEW AND ECONOMICS

In 1881 Jaques d'Arsonval published his thoughts on the possibility of constructing a steam power generator that made use of the temperature difference between the surface water and the deep water in the tropical seas.[6] In 1930 Georges Claude actually constructed this type of SSPP at Matanzas Bay, Cuba.[7] This plant had a 22 KW_{elect} output. This experimental SSPP operated by taking advantage of a 14°C thermal gradient. The cold water was brought up from 700 meters below the sea surface in a 1.6 meter diameter pipe which extended to 2 km offshore.

In the 1950's a French corporation, Energie Electrique de la Cote d'Ivoire, planned the construction of an SSPP at Abidjan Ivory Coast. This plant was never put into operation, contrary to the report in Reference 8. This SSPP was to have produced steam power based on a 20°C thermal gradient. The cold water would have been brought up from a depth of 430 m, 4 km offshore and pumped through a 2 m diameter pipe. The flow through the cold water pipe was designed to operate at 2 m/sec. However, approximately 25% of the power produced by this SSPP would have been consumed by the operations of the SSPP itself.

Ocean thermal gradient power production, along with wind power generation will become increasingly attractive, and even necessary, as we approach the 21st century. Thus, there will be great demand for fossil fuels, but not necessarily for the purposes of power generation, Oil, coal and natural gas will be needed by the various chemical industries for the production of lubricants, paints, plastics, synthetic products, food, and fertilizer.[9]

The comparative attractiveness of the SSPP as opposed to other solar energy schemes (even without considering desalination and mariculture) is due to cost. The SSPP does not need acres of expensive solar collectors or expensive storage units for nights and cloudy days. The ocean continuously acts as a collector and as a heat storage unit. SSPPs are also economically attractive when compared to conventional fossil fuel and nuclear power plants. The Andersons estimate that a SSPP can be constructed for $200 per kilowatt.[10] New nuclear powered plants cost $700 per kilowatt and new coal fired plants cost more than $550 per kilowatt. In addition the fuel costs for fossil and nuclear plants are rapidly increasing (SSPP fuel is free) and should be taken into consideration. Table 1 gives some cost details for comparative power systems.[11]

Ocean thermal gradient power production has the potential for supplying 100% of the U.S. electric energy requirements in the not too distant future. By the year 2000 it could supply up to 5% of those requirements, and by the year 2020, 10% or more. To get some idea of the magnitude of the energy available consider that in 15 minutes the earth intercepts enough radiant energy from the sun to equal the amount of energy that is consumed worldwide in the form of fossil and nuclear fuels each day. In less than four days, an amount of energy equal to all of the earth's fossil fuel reserves is intercepted.

There are two distinct SSPP types with respect to site selection: the shore-based system and the ocean-based system. The typical shore-based system would be located on the coast lines of Florida, Puerto Rico, Hawaii, etc. However, the availability of suitable coastline constrains the gross quantity of power that shore-based systems can generate. Ocean-based systems will typically be constructed so as to be a self contained floating or tethered platform submerged below the surface of the sea, but still above the thermocline. The optimum location for such a plant is in tropical waters, 23°N to 23°S.[11] Transmission and storage problems may limit the amount of power delivered by ocean-based plants. For example, if SSPPs were to supply 10% of the U.S. energy requirements by the year 2020, about 0.3 million tons of hydrogen would have to be shipped each day. That is the equivalent of 30 shiploads per day where each

Table 1

Comparison of Cost of Electricity for Various Types of Systems
(In terms of estimated dollar values for period indicated)

Type of System	Initial Investment, Power Generation			Fuel Costs[5]			Initial Investment, Conversion & Storage			Other Costs		
	1980	1990	2000	1980 to 2000	1990 to 2010	2000 to 2020	1980	1990	2000	1980 to 2000	1990 to 2010	2000 to 2020
Hydro-Electric (With H_2O Storage)	$277 to[1] $870/kw	$312 to[1] $982/kw	$392 to[1] $1230/kw	–	–	–	–	–	–	$772 to[7] $2118/kw	$970 to[7] $2661/kw	$970 to $2661/kw
Gas-Fired	$277/kw[1]	$312/kw[1]	$392/kw[1]	$1482/kw	$2156/kw	$2451/kw	–	–	–	$1053/kw[7]	$1323/kw[7]	$1323/kw[7]
Oil-Fired	$323/kw[1]	$364/kw[1]	$458/kw[1]	$1443/kw	$2132/kw	$2451/kw	–	–	–	$1207/kw[7]	$1517/kw[7]	$1517/kw[7]
Coal-Fired	$313/kw[2]	$352/kw[2]	$442/kw[2]	$955/kw	$1443/kw	$1666/kw	–	–	–	$1174/kw[7]	$1475/kw[7]	$1475/kw[7]
Nuclear-Fueled	$396/kw[3]	$447/kw[3]	$560/kw[3]	$328/kw[6]	$412/kw[6]	$412/kw[6]	–	–	–	$1698/kw[8]	$2134/kw[8]	$2134/kw[8]
Organic Mat.-Fired	$313/kw	$352/kw	$442/kw	$0 to $1288/kw	$0 to $1622/kw	$0 to $1622/kw	–	–	–	$1174/kw[9]	$1475/kw[9]	$1475/kw[9]
Solar-Thermal (Without Storage)	$800/kw	$700/kw	$600/kw	–	–	–	–	–	–	$2715/kw[9]	$2660/kw[9]	$1820/kw[9]
Solar-Thermal (With Thermal Storage)	$800/kw	$700/kw	$600/kw	–	–	–	$232/kw	$261/kw	$328/kw	$3477/kw[9]	$3616/kw[9]	$2775/kw[9]
Ocean ΔT (Without Storage)	$346 to $692/kw	$390 to $780/kw	$490 to $980/kw	–	–	–	–	–	–	$1281 to[9] $2416/kw	$1610 to[9] $3036/kw	$1610 to[9] $3036/kw
Wind Energy (Without Storage; Or with H_2O Storage)	$173 to $346/kw	$195 to $390/kw	$245 to $490/kw	–	–	–	–	–	–	$714 to[9] $1281/kw	$897/kw[9] $1610/kw	$897 to[9] $1610/kw
Wind Energy (With H_2 Storage)	$173 to $346/kw	$195 to $390/kw	$245 to $490/kw	–	–	–	$346/kw	$390/kw	$490/kw	$1848 to[9] $2416/kw	$2323 to[9] $3036/kw	$2323 to[9] $3036/kw
Photovoltaic (Without Storage)	$1700/kw[4]	$633/kw[4]	$368/kw[4]	–	–	–	–	–	–	$5673/kw[9]	$2415/kw[9]	$1145/kw[9]
Photovoltaic (With H_2 Storage)	$1700/kw[4]	$633/kw[4]	$368/kw[4]	–	–	–	$232/kw	$261/kw	$328/kw	$6435/kw[9]	$3372/kw[9]	$2100/kw[9]
Photovoltaic Plus Wind Energy (With H_2 Storage)	$937 to $1023/kw	$414 to $511/kw	$307 to $429/kw	–	–	–	$74/kw	$84/kw	$105/kw	$3409 to[9] $4170/kw	$1919 to[9] $2275/kw	$1273 to[9] $1628/kw

Table 1 (continued)

Type of System	Total 20-Year Cost			Plant Factor			Average Price of Electricity at Plant		
	1980 to 2000	1990 to 2010	2000 to 2020	1980 to 2000	1990 to 2010	2000 to 2020	1980 to 2000	1990 to 2010	2000 to 2020
Hydro-Electric (With H_2O Storage)	\$1049 to \$2988/kw	\$1282 to \$3643/kw	\$1362 to \$3891/kw	0.60	0.60	0.60	10 m/kwh to 28 m/kwh	12 m/kwh to 35 m/kwh	13 m/kwh to 37 m/kwh
Gas-Fired	\$2812/kw	\$3791/kw	\$4166/kw	0.60	0.60	0.60	27 m/kwh	36 m/kwh	40 m/kwh
Oil-Fired	\$2973/kw	\$4013/kw	\$4426/kw	0.60	0.60	0.60	28 m/kwh	38 m/kwh	42 m/kwh
Coal-Fired	\$2442/kw	\$3260/kw	\$3583/kw	0.60	0.60	0.60	23 m/kwh	31 m/kwh	34 m/kwh
Nuclear-Fueled	\$2442/kw	\$2993/kw	\$3106/kw	0.60	0.60	0.60	23 m/kwh	28 m/kwh	30 m/kwh
Organic Mat.-Fired	\$1487 to \$2775/kw	\$1827 to \$3449/kw	\$1917 to \$3539/kw	0.60	0.60	0.60	14 m/kwh to 26 m/kwh	17 m/kwh to 33 m/kwh	18 m/kwh to 34 m/kwh
Solar-Thermal (Without Storage)	\$3515/kw	\$3360/kw	\$2420/kw	0.25	0.25	0.25	80 m/kwh	77 m/kwh	55 m/kwh
Solar-Thermal (With Thermal Storage)	\$4509/kw	\$4577/kw	\$3703/kw	0.25	0.25	0.25	103 m/kwh	104 m/kwh	84 m/kwh
Ocean ΔT (Without Storage)	\$1627 to \$3108/kw	\$2000 to \$3816/kw	\$2100 to \$4016/kw	0.60	0.60	0.60	15 m/kwh to 30 m/kwh	19 m/kwh to 36 m/kwh	20 m/kwh to 38 m/kwh
Wind Energy (Without Storage; or With H_2O Storage)	\$887 to \$1628/kw	\$1092 to \$2000/kw	\$1142 to \$2100/kw	0.30	0.30	0.30	17 m/kwh to 31 m/kwh	21 m/kwh to 38 m/kwh	22 m/kwh to 40 m/kwh
Wind Energy (With H_2 Storage)	\$2367 to \$3108/kw	\$2908 to \$3816/kw	\$3058 to \$4016/kw	0.30	0.30	0.30	45 m/kwh to 59 m/kwh	55 m/kwh to 72 m/kwh	58 m/kwh to 76 m/kwh
Photovoltaic (Without Storage)	\$7373/kw	\$3048/kw	\$1512/kw	0.25	0.25	0.25	168 m/kwh	69 m/kwh	34 m/kwh
Photovoltaic (With H_2 Storage)	\$8367/kw	\$4266/kw	\$2796/kw	0.25	0.25	0.25	190 m/kwh	97 m/kwh	64 m/kwh
Photovoltaic Plus Wind Energy (With H_2 Storage)	\$4420 to \$5267/kw	\$2417 to \$2870/kw	\$1685 to \$2162/kw	0.275	0.275	0.275	92 m/kwh to 110 m/kwh	50 m/kwh to 60 m/kwh	35 m/kwh to 45 m/kwh

Footnotes for Table 1

1. Data for 1968 adjusted to 1970 by factor of 1.07. Then adjusted to 1980, 1990 and 2000 by factors of 1.73, 1.95 and 2.45, respectively.[12]

2. Data for 1965 adjusted to 1970 by factor of 1.14 plus pollution control cost of $56/kw (from Simpson, ibid). Then adjusted to 1980, 1990 and 2000 by factors of 1.73, 1.95 and 2.45, respectively.[13]

3. Data for 1968[12] adjusted to 1970 by factor of 1.07 plus pollution control cost of $15/kw.[13] Then adjusted to 1980, 1990 and 2000 by factors of 1.73, 1.95 and 2.45 respectively.

4. Assumes investment cost of $2.70 per square foot (1970 dollars) for solar cell array; 4% efficiency, x5 light concentration.

5. Fuel cost based upon FPC 1968 data, adjusted to 1970 by factor of 1.07, and adjusted to 1980 to 2000, 1990 to 2010 and 2000 to 2020 using scenario.

FPC Price Estimates (1970 dollars)	Coal	Oil	Gas
1968	25.5 cents/MBTU	32.8	25.1
1970	27.3	35.1	26.9
1975	32.75	44.1	61.9
1985	41.0	63.2	67.3
2000	54.6	80.7	80.7

Plant efficiency is assumed to be equal to 0.1 MWh/MBTU = 30%

20 yr. production = (0.6) (8760) (20) = 105.120 MWh/kw = 1072.2 MBTU/kw per kw

6. Fuel cost for nuclear (in 1970 dollars) is assumed to be constant over time.

7. Based on fixed charge rate given in FPC (I-19-6)

   Coal, Oil, and Gas = 14.2% per year
   Hydro-electric = 9.7% per year
   Nuclear = 14.7% per year
   Nuclear Fuel = 12.4% per year
   Annual O&M cost rates based upon FPC data, i.e. $3.00 per kw;
   Administrative and General Expenses = $0.75/kw; and Working Capital
   = (3.4%) (10.2%) x (Investment) = 0.35% x (Investment)
   Cost of capital
   % of investment needed per working capital

8. Assumed life of nuclear fuel = 5 years.

9. Based on fixed charge rate of 14.2% per year (i.e. same as coal, oil and gas, see above).

ship carries 10,000 tons of hydrogen per trip. Underwater hydrogen pipelines might be feasible, or direct dc electric current transmission with dc to ac converters on shore, may be the most economical solution to the energy transportation problem.

In addition to the shore-based, ocean-based controversy, there are many different points of view regarding whether to build a closed cycle or an open cycle SSPP, and if a closed cycle SSPP is built what is to be the working fluid. Figures 3 and 4 (from Ref. 14) show one version of a closed cycle SSPP. Figure 5, along with Tables 2 and 3, give yet another design and cost estimates for a closed cycle SSPP.[15] Another version of the closed cycle SSPP is shown in Figure 6.[11] An open cycle system is illustrated in Figure 7.[11] This is essentially the system designed by Claude around 1925.[7]

At this point it is worthwhile to describe the NSF supported designs for the SSPP. The first SSPP design we will explore is the well known Zener concept. Zener has been very effective in popularizing his ideas in the popular scientific literature.[16,17] The Zener, or Carnegie-Mellon University (CMU) SSPP is a 100 megawatt plant.[18] The cold water pipe for this plant will be 2000 feet long and 60 feet in diameter and bring 10 million gallons per minute up to the SSPP condensers. The CMU plan also calls for 8 ft/sec water flow through the heat exchanger tubes. These tubes will be 10 ft long and one inch in diameter.

The thermal gradient that will operate this SSPP is assumed to be 20°C of which 10°C will be dissipated in forcing the heat to the working fluid. This leaves 10°C available for the heat engine and yields an efficiency of a bit over 2%. The weight of the tethering cable is estimated to be 800,000 lbs. Table 4 compares the cost of the CMU SSPP with the Anderson concept referred to above. The life of the CMU SSPP is assumed to be 25 years with maintenance and the heat exchangers are assumed to be the life limiting components. Further details of the CMU SSPP may be found in Reference 19. The details of the CMU design remain rather sparse. The work thus far generated has concentrated on somewhat narrow problems that have been gone into in great detail. What is needed by the CMU team is an integrated system design of their SSPP to at least obtain a preliminary configuration and some details of the interfacings of the various subsystems. With this accomplished a trade-off analysis can be performed to optimize subsystems and components.

The other proposed SSPP design is due to W. Heronemus and his group at the University of Massachusetts (UMASS). A schematic of the UMASS design is shown in Figure 4. The UMASS SSPP is designed to be placed in the Gulf Stream 15 miles east of the Collier Building of the University of Miami. The UMASS system assumes a thermal working gradient of 31.5°F and an efficiency of 1.8%. Propane is to be the working fluid for this 400 megawatt SSPP. The cold water

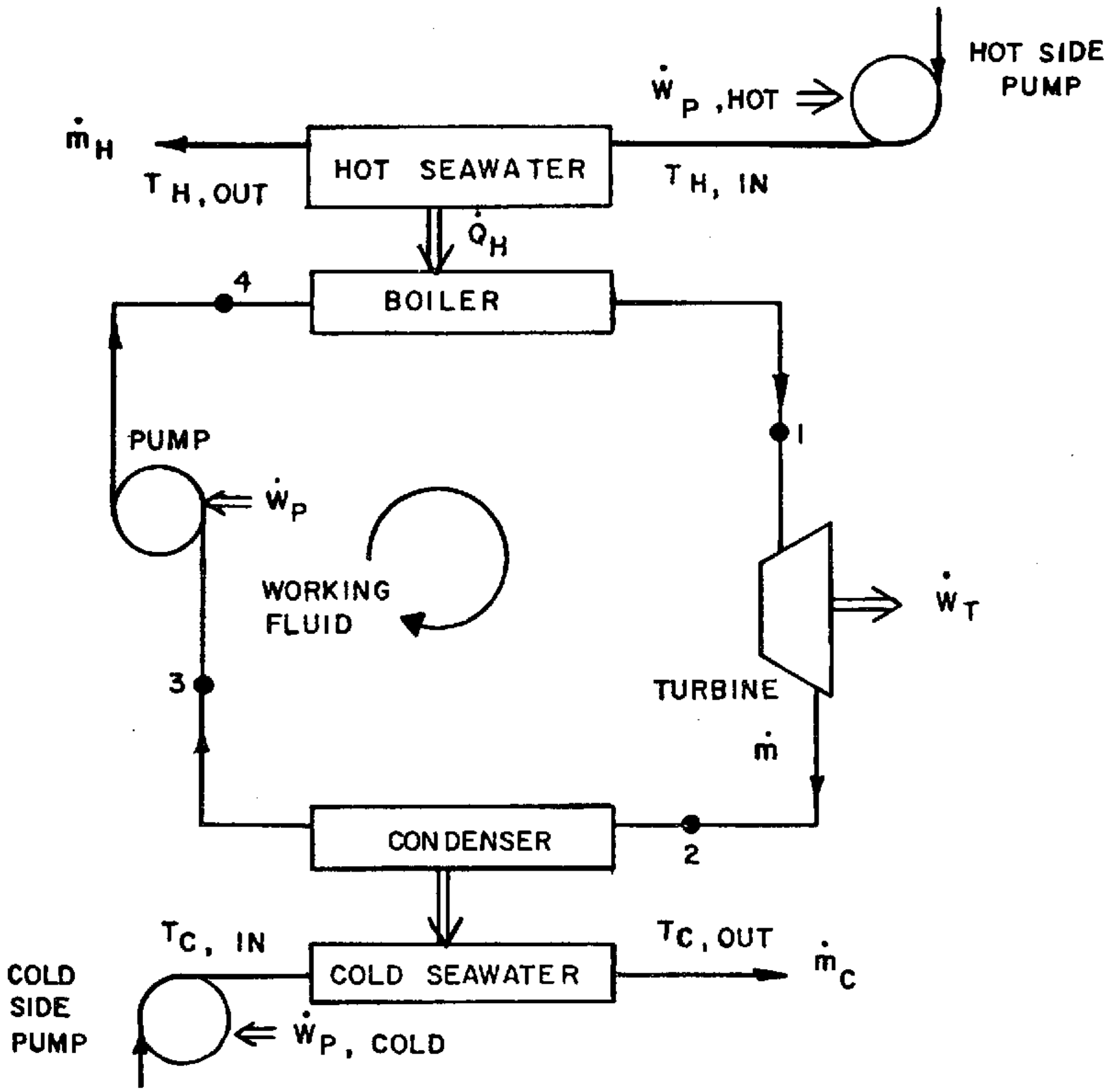

Figure 3. Closed Cycles SSPP

pipe will be fabricated out of aluminum or mild steel and the plate and fin heat exchangers will be made of Cu Ni.

The UMASS SSPP will have 16 power units and 20 vertical heat exchangers. A 40 year life is assumed with a cost of \$300/kw to \$750/kw delivered at the beach. It was pointed out that the turbine would cost \$65/kw if propane is selected as the working fluid, but only \$35/kw if the working fluid is ammonia. Further details on the UMASS SSPP can be found in References 20, 21, 22, 23, and 24.

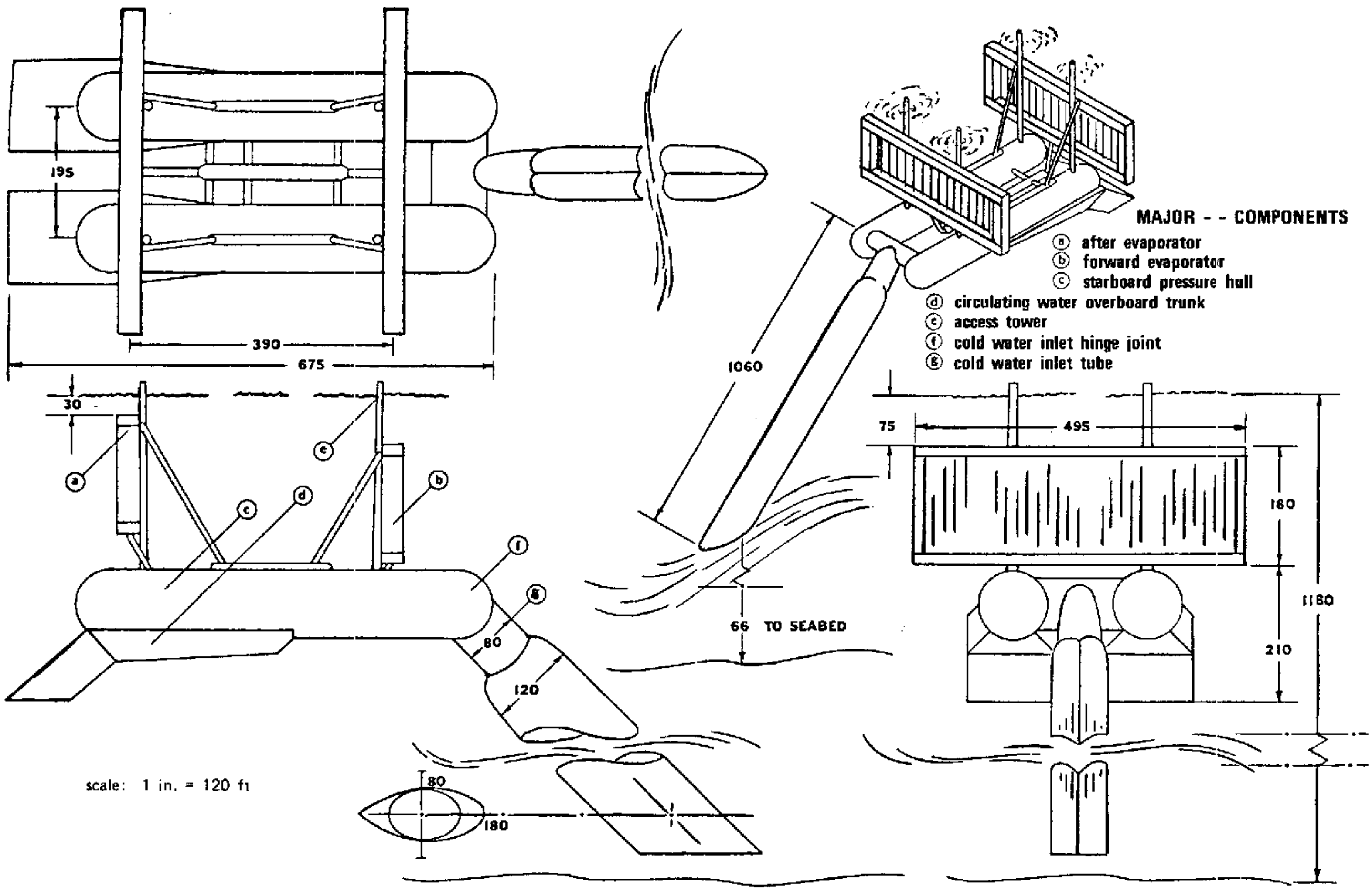

Figure 4. Schematic of the UMASS Design

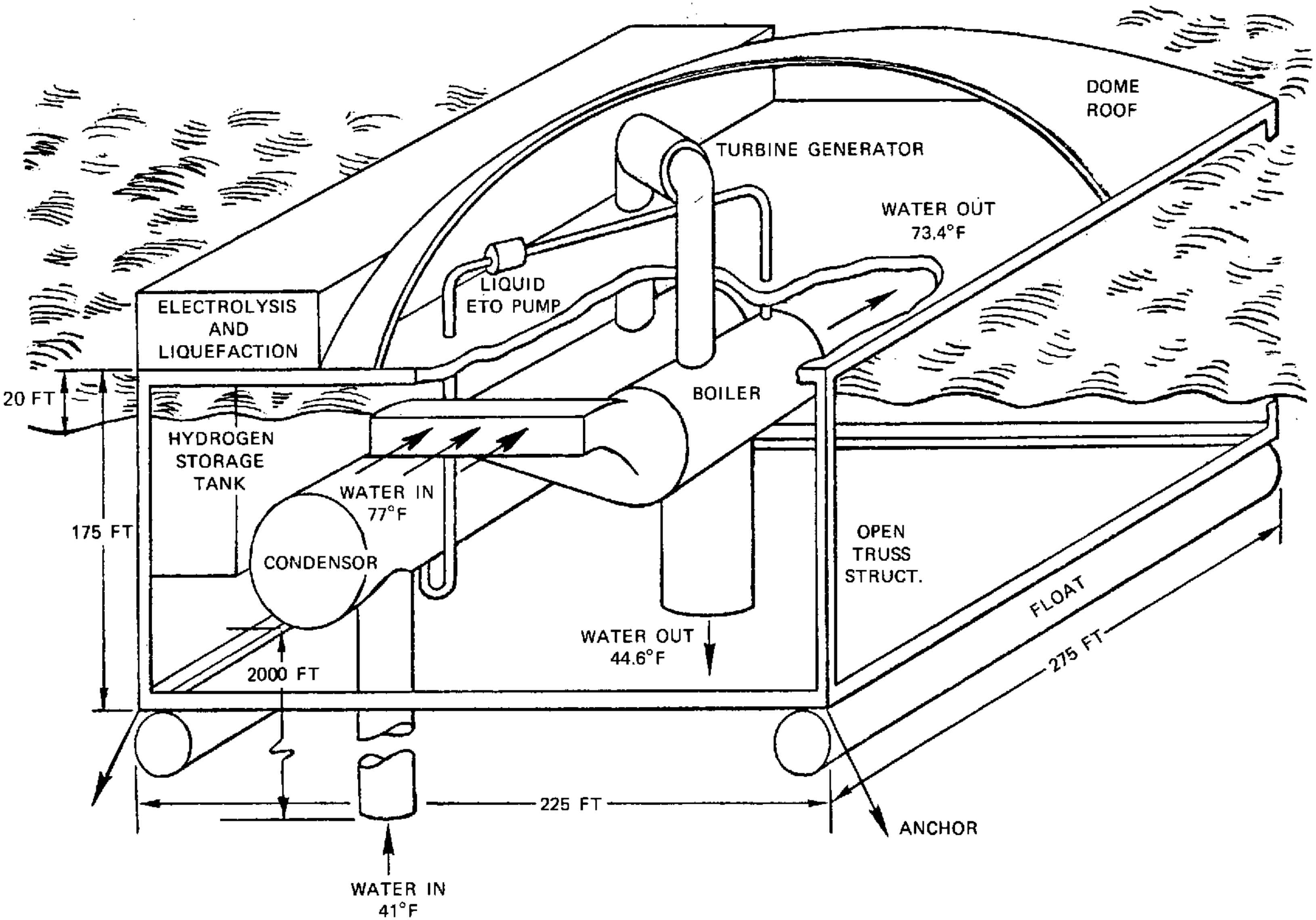

Figure 5. Solar Sea Power Plant (100 MW) Schematic

Table 2

Preliminary Cost Estimate for the SSPP

Working Medium	Ammonia	Propane	Ethylene Oxide
Component	Cost (Millions of dollars)		
Boiler	4.2	4.3	4.3
Boiler feed tube	0.01	0.01	0.01
Boiler water collector tube	0.4	0.4	0.3
Condenser	7.5	13.8	10.6
Condenser exit water deflector	0.2	0.2	0.2
Condenser cold water pipe	3.4	3.2	2.9
Turbine piping	0.02	0.03	0.03
Working medium	0.24	0.20	0.39
Turbine generator	2.8	6.5	20.1
Liquid pumps	1.0	1.2	1.1
Platform	5.0	5.1	5.1
Miscellaneous piping and auxiliary items (10%)	2.5	3.5	4.5
TOTAL	$27.3 M	$38.4 M	$49.5 M
Net power output* (MW)	92.3	85.1	89.9
Plant cost per 100 MW (millions of dollars)	29.6	45.1	55.1

*Rankine cycle net power (100 MW) minus pumping power.

Table 3

Cost of Electric Power at SSPP Plant

	Ammonia	Propane	Ethylene Oxide
Construction Cost, 100 MW Plants			
Initial cost ($M)	29.6	45.1	55.1
Amortized cost, 25 yr @ 8% ($M)	68.5	104.3	127.4
Amortized cost ($/kw)	685.0	1043.0	1274.0
Amortized cost (mill/kwh)	3.1	4.8	5.8
Insurance (1% of initial cost, mill/kwh)	0.3	0.5	0.6
Subtotal, fixed cost at 100% capacity (mill/kwh)	3.4	5.3	6.4
Operating costs, 30 men at* $33 K/m-hr (mill/kwh)	1.2	1.2	1.2
Total cost (mill/kwh)	4.6	6.5	7.6

*Arbitrary estimate – may be high.

The design of a land-based system is not as complex as that of an ocean-based system and both the CMU and UMASS SSPP concepts can be applied to land-based systems with little redesign of the working components. In fact, we have had a lot more experience with land-based piping systems that are applicable to SSPP design. The Ivory Coast pipeline was designed to be 4 miles long; there are many sewer outfall pipes longer than 4 miles made out of concrete. On Cyprus there is a 2 mile long plastic waste water pipe that was installed by un-reeling the pipe and simply anchoring it to the sea floor.

The Japanese are also interested in the design of an ocean based SSPP.[25] Shown in Figure 8 is a preliminary conceptual design for a 1,500 KW_{elect} SSPP. The specifications for the SSPP are shown in Table 5 for two working fluids. The cost data for this SSPP with respect to these working fluids is shown in Table 6.

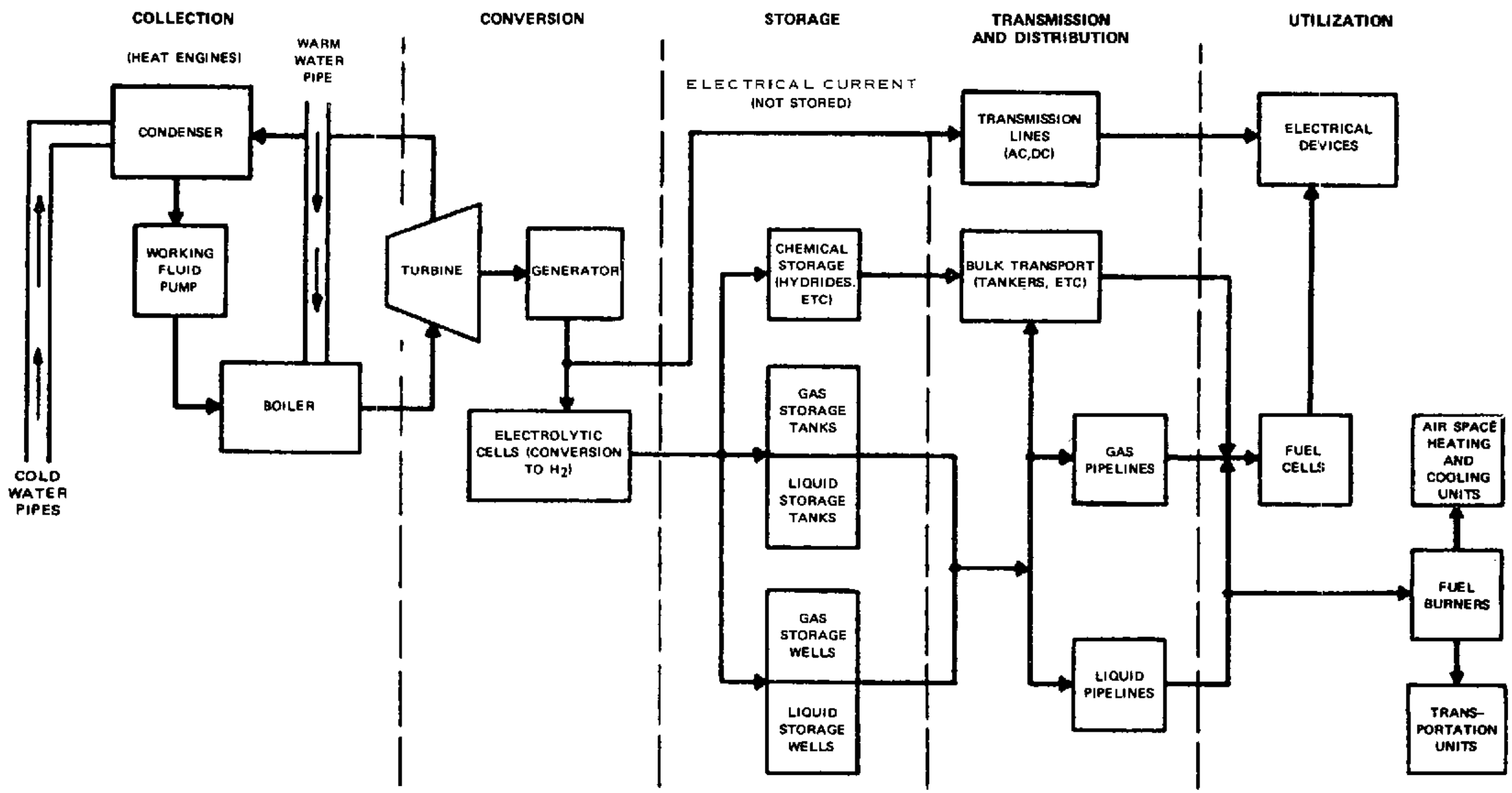

Figure 6. Flowchart for Alternative Ocean Thermal Gradient Systems

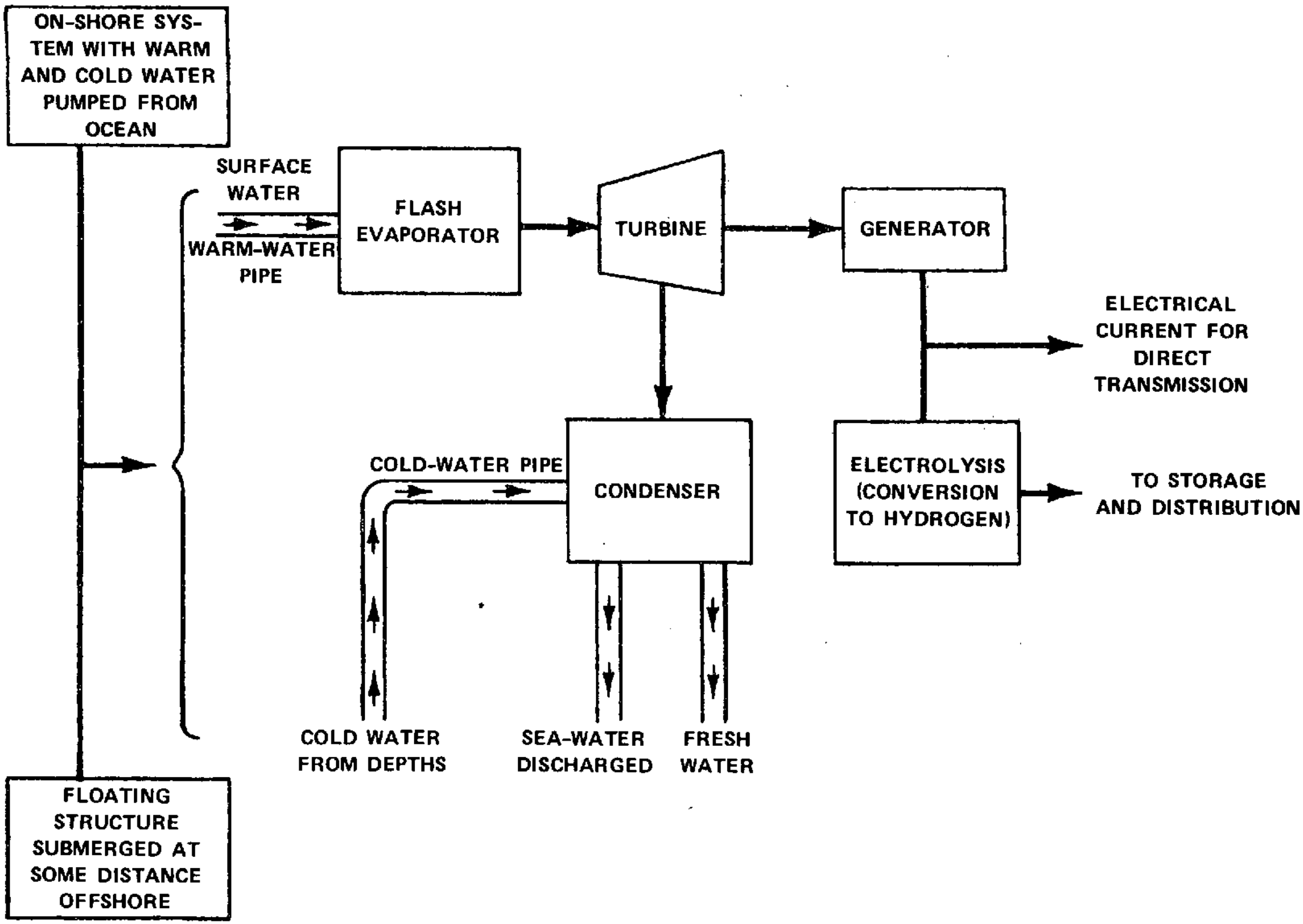

Figure 7. Schematic of Open Cycle Variant of Ocean Thermal Gradient Collection and Conversion

Table 4

100 MW SSPP

	Anderson Thousands $	CMU Thousands $
Boiler Evaporator	2,400	1.600
Turbines	720	1,000
Generator	1,235	1,800
Boiler water pump	820	1,000
Condenser	2,450	1,600
Cond. water pump	640	1,000
Warm water pipe	131	250
Cold water pipe	708	1,000
Inlet screens	304	450
Auxiliary pumps	152	230
	9,560	9,930
Auxiliaries	443	650
Structure	4,210	6,000
Cold pipe	262	400
	14,475	16,980
Miscellaneous	2,172	3,020
	16,647	20,000

Comparison of capital cost per kilowatt

Nuclear	$ 802
Fossil	1169
SSPP	165
Hydrogen fuel cell (for shipping SSPP power)	694

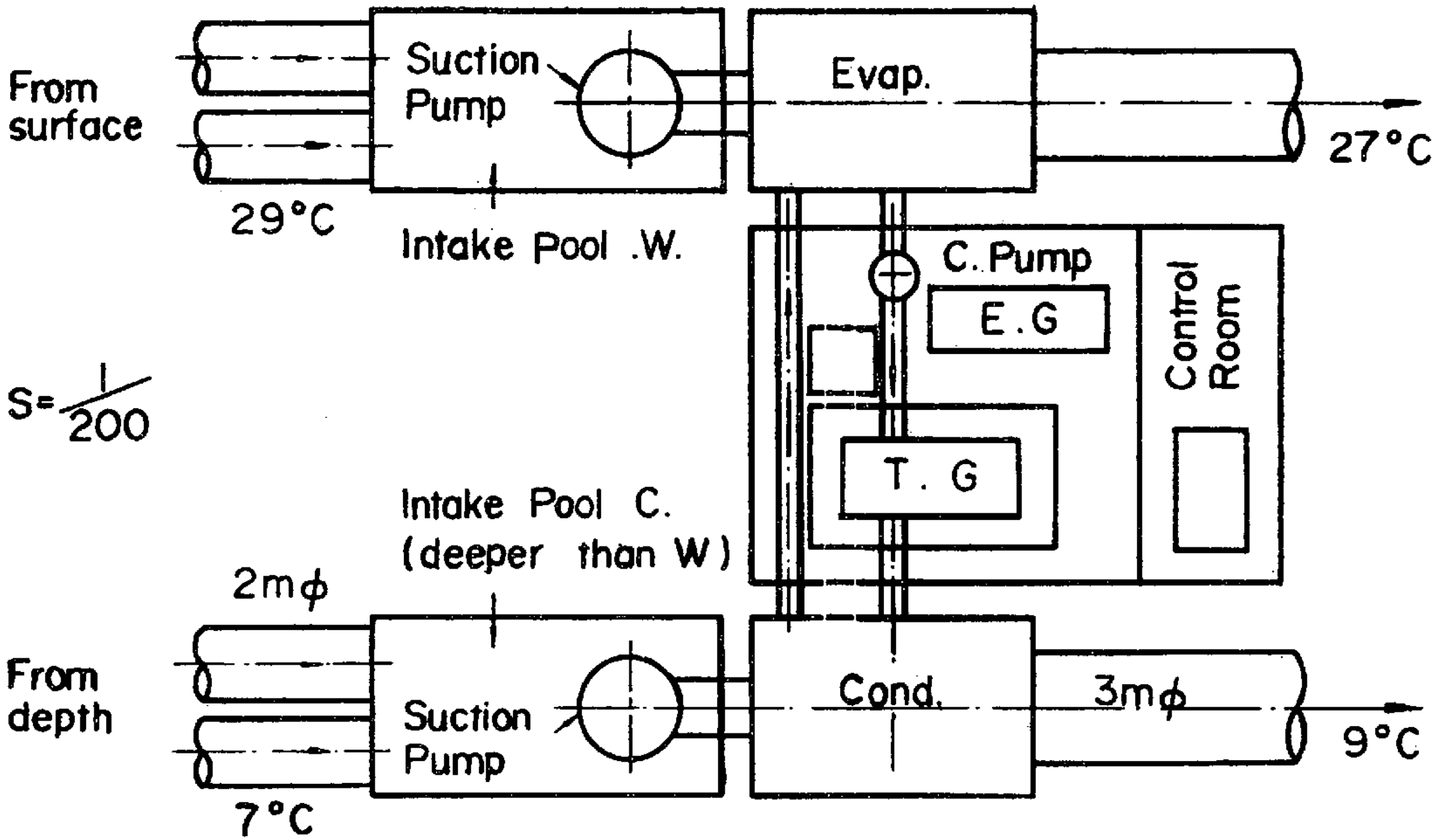

Figure 8. Plan of the 1500 kw Experimental SSPP

Table 5

Specification of the Experimental 1500kw SSPP

Items \ Working Fluids	NH_3	R-114
Turbine and Generator		
Generator output (kw)	1,500	1,500
Turbine (RPM)	3,600	3,600
Blade height (mm)	~60	~410
Working fluid flow (ton/h)	173	1,270
Working fluid volume (ton)	220	490
Evaporator and Condenser		
Evap. heat exchange (G cal/h)	50.8	43.5
Cond. heat exchange (G cal/h)	49.5	42.0
Warm water temp (°C)	29	29
Cold water temp (°C)	7	7
Intake water		
Warm side (m^3/h)	25,900	22,200
Cold side (m^3/h)	25,200	21,400

Items \ Working Fluids	NH	R-114
Intake Equipments		
Pipes (FRP)	1 m ϕ x 9 (2 m ϕ x 2)	1 m ϕ x 9 (2 m ϕ x 2)
Cold pipe length (m)	1,000	1,000
Pump power (kw)		
Cold side	330	300
Warm side	120	110
Working fluid	40	30
Civil Works		
SSPP plant (m^2)	150	150
Concrete works (m^3)	950	950
Sub-merged		
Concrete works (m^3)	500	500
FRP anchor (ton)	50	50
FRP works (man. day)	300	300
Others		

Table 6

Rough Estimation of the Cost of Experimental 1500kw SSPP
(by present technologies)

Cost \ Working Fluids	NH_3	R-114
Turbine and Generator	2.2×10^5\$	2.3×10^5\$
Evaporator and Condenser (shell and tube type)	9.7×10^5\$	10.8×10^5\$
Pumps and Motors	2.4×10^5\$	2.6×10^5\$
Intake pipes (FRP)	15.3×10^5\$	15.3×10^5\$
Electric Equipments	1.7×10^5\$	1.7×10^5\$
Water Pipe Screen	0.3×10^5\$	0.3×10^5\$
Working Fluid/Pump	0.2×10^5\$	0.2×10^5\$
Working Fluid	0.4×10^5\$	12.7×10^5\$
Civils	10.4×10^5\$	10.4×10^5\$
Reserve	2.1×10^5\$	3.3×10^5\$
Total Construction Cost	44.6×10^5\$	59.1×10^5\$
Generated Power per Year	7.53×10^6 kwh	7.9×10^6 kwh
Unit Construction Cost	3,000 \$/kw	3,900 \$/kw
Unit Power Cost (at transmission terminal)	89 mil/kwh	112 mil/kwh

This plant is designed to be placed in tropical waters. It is assumed that the surface waters are at a temperature of 29°C. The cold water at the intake pipe is assumed to be at 7°C. Note that small changes in the cold water temperature produce relatively large changes in power production as shown in Table 7.

Some further information on the Japanese ideas on SSPPs may be found in References 26 and 27.

Table 7

Dependency of Power Output to Cold Water Temperature

Cold water temperature	7°C		8°C		9°C	
Items \ Working Fluids	NH_3	R-114	NH_3	R-114	NH_3	R-114
Output power (kw) (at the generator terminal)	1,500	1,500	1,380	1,410	1,250	1,320
Unit power cost (mil kwh) (at the transmission terminal)	89	112	97	114	113	124

IV. MARICULTURE AND SITING

To obtain some insights into the siting problem, consider first the Japanese experience.[25] After studying the entire Japanese coastline it was concluded[28] that while the water temperatures below 200 m are less than 10°C almost everywhere, the surface temperatures show great variation with the season as shown in Figure 9. Situations of this type are also characteristic of much of the U.S. coastal waters. Note, however, the relative attractiveness of the Pacific islands such as Truk and Guam as shown in Figure 9.

Now let us consider the North Atlantic Ocean and the entire eastern seaboard of the U.S.[29,30] Figure 10 shows the variations in surface and sub-surface temperatures month by month. Significant temperature variations in the surface temperatures comparable to the Japanese situation are observed. The annual range of the Atlantic coast temperatures is greatest at the north end of the coast: 2.8°C to 15.5°C, while the smallest temperature difference at the surface: 24.4°C to 29.6°C is observed near Miami. This 5.2°C difference is important because the Miami site has been proposed as a potential SSPP site. This

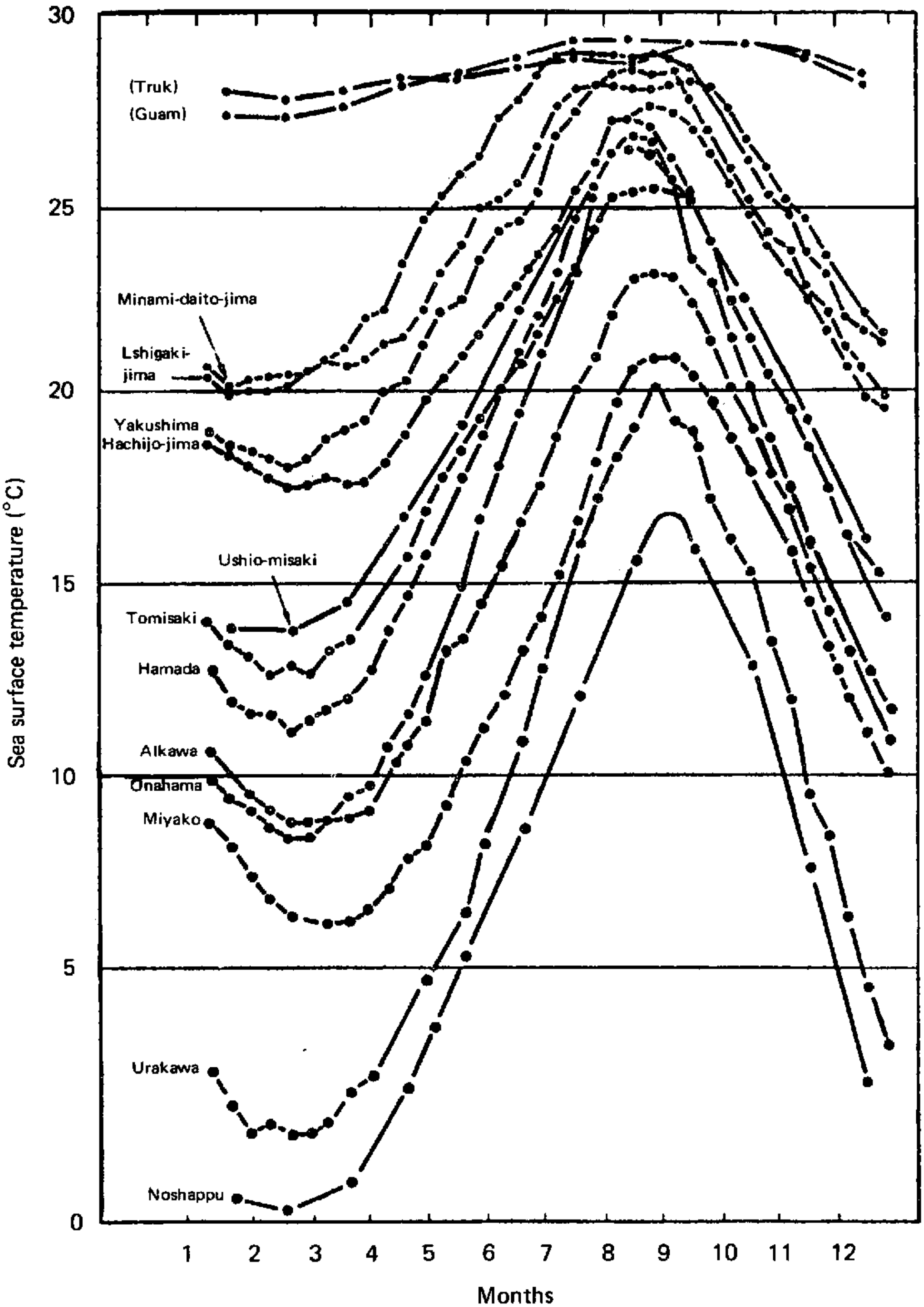

Figure 9. Monthly Variation of Sea-surface Temperature in Japan and Tropics

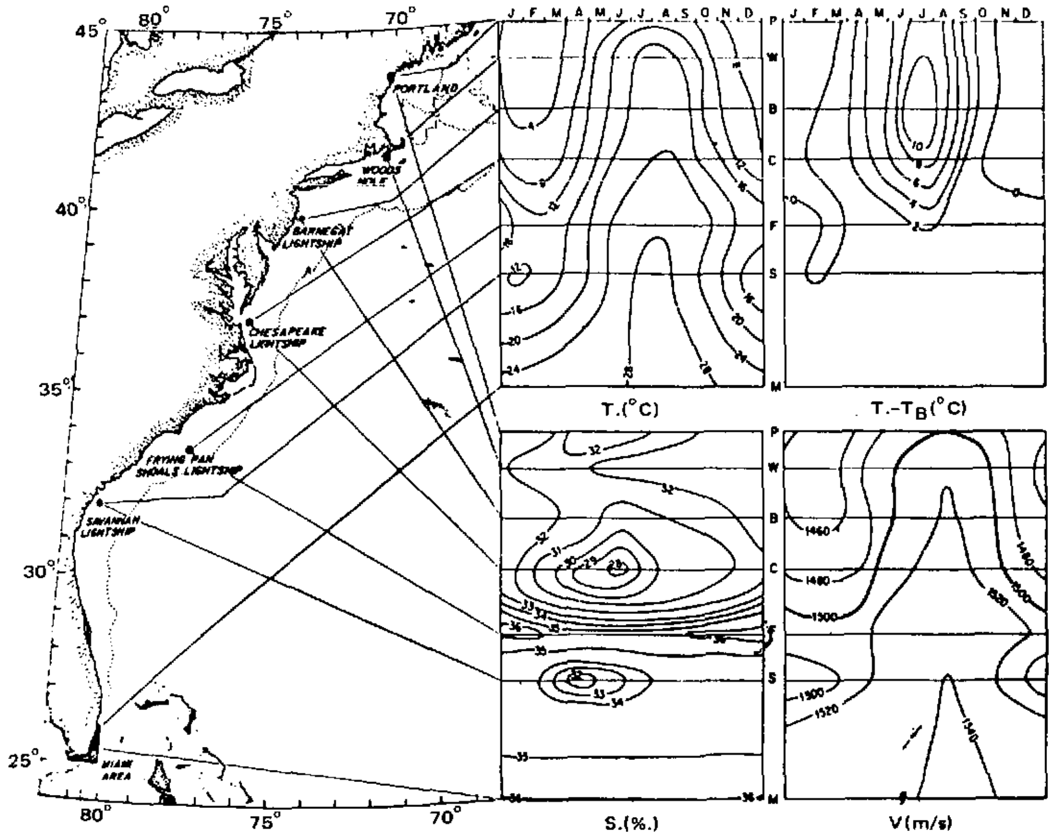

Figure 10. Annual Cycle of Monthly Average Surface Temperature, Bottom Temperature, Surface Salinity, and Computed Surface Sound Velocity at Five Lightships and Lighthouses and for a 1° Square of Miami Area. Based on unpublished data of Woods Hole Oceanographic Institution files (1958-1961 for lightships and lighthouses and 1940-1961 for Miami area).[29]

temperature difference can greatly influence the efficiency of an SSPP and even cause an SSPP demonstration project to fail. Note the advantage of a tropical SSPP with a maximum temperature difference of only 2°C. Figure 9 shows Truk and Guam to be better SSPP sites than Miami on the basis of ΔT considerations. Figure 11 shows some further information on temperature-salinity variations. On the other hand if one is constrained to build an SSPP near the U.S. mainland, Miami is the best site available on the east coast. Figure 12 shows the surface temperatures during the critical month February indicating that one observes temperatures up to 24°C at Miami. Notice that Figures 12 and 13 tend to rule out the possibility of a horizontal temperature gradient SSPP. The temperature differences at various places off the North Atlantic coast in February appear to be sufficient (marginally) to achieve a 1.25% efficiency. However,

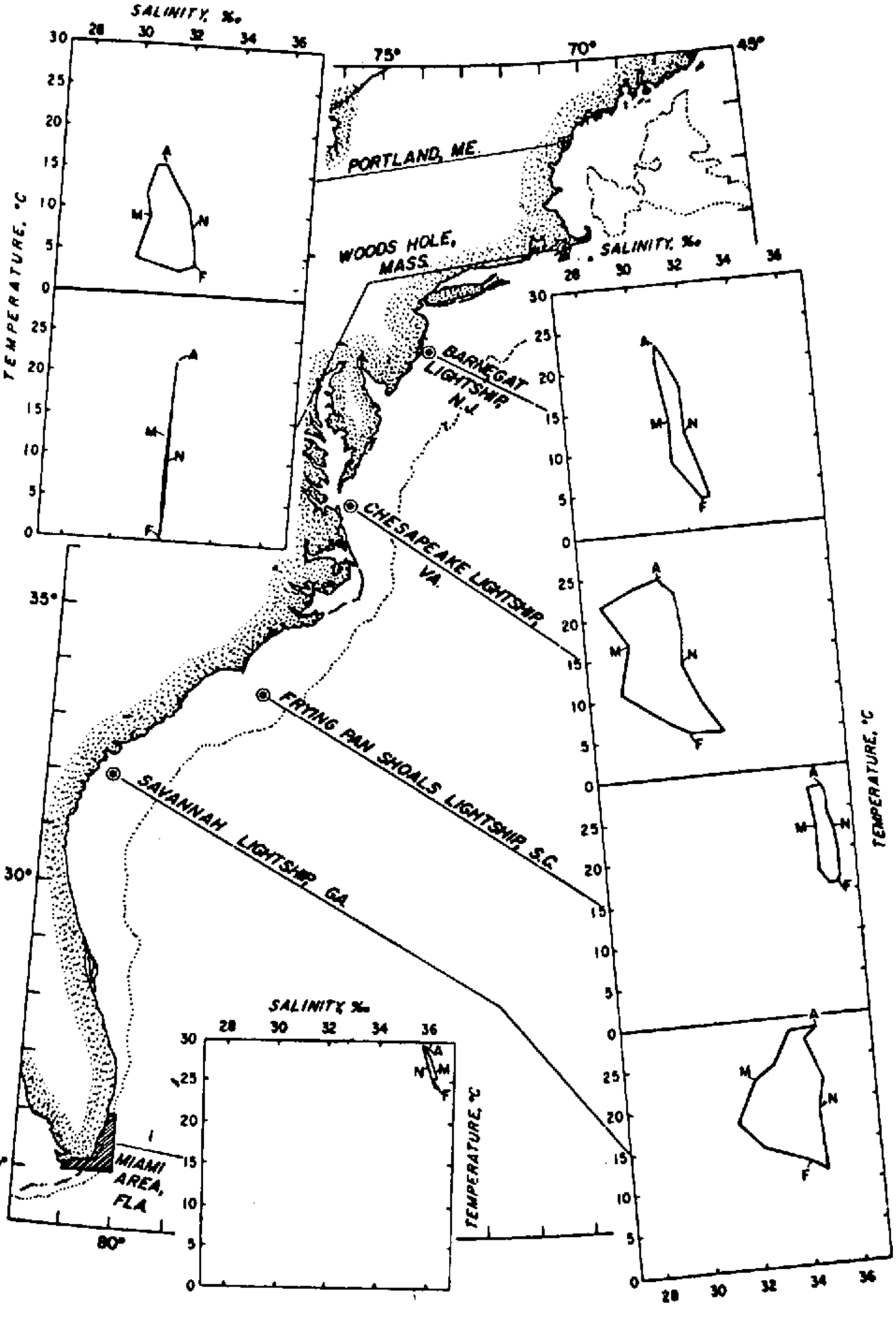

Figure 11. Polygons Showing Monthly Average Salinities and Temperatures for 1956-61 (except for Miami, which has a longer period). Based on same data as used for Figure 10.[29]

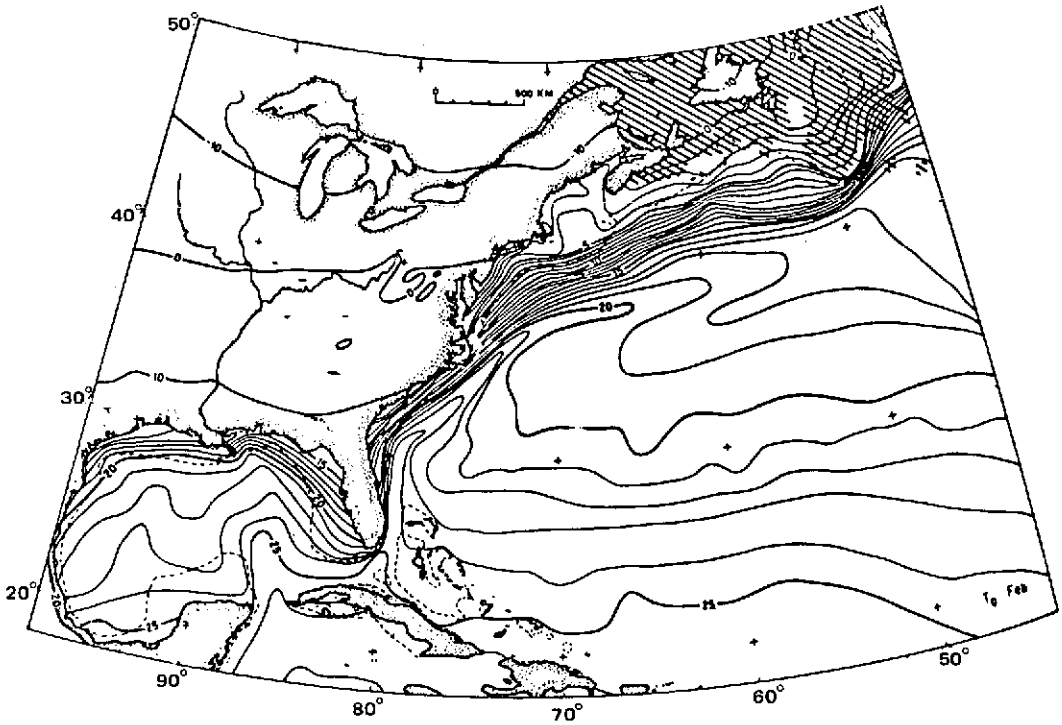

Figure 12. Surface Temperature of Western North Atlantic Ocean During February. Based upon unpublished data of 1940 to 1970 in files of Woods Hole Oceanographic Institution: 13,900 observations within about 200km of shore and 11,800 observations farther at sea. Isotherms on land are from Climatology Unit (1943), and areas where icebergs or heavy sea ice were seen between 1911 and 1940 (cross-hatched) are from Weaver (1946).[29]

look at Figure 13. In August these temperature differences all but disappear. There is a gradual decrease in the temperature difference from February to August and a horizontal gradient SSPP would be efficient for only two months of the year. It is also interesting to note that the surface temperatures near the Gulf coast in February are about 15°C; insufficient to operate an SSPP.

Thus the only viable potential SSPP site off the coast of the U.S. appears to be the Miami site in the Gulf Stream or Florida current. That part of the Gulf Stream between the Strait of Florida and Cape Hatteras is usually called the Florida current. Another reason for selecting Miami as a prime site is the temperature behavior of the subsurface waters as shown in Figure 14. Only off Miami does the temperature decrease with depth throughout the year, elsewhere it decreases only during the summer. At a depth of only 200 meters one begins to find temperatures of 8°C at the Miami site.

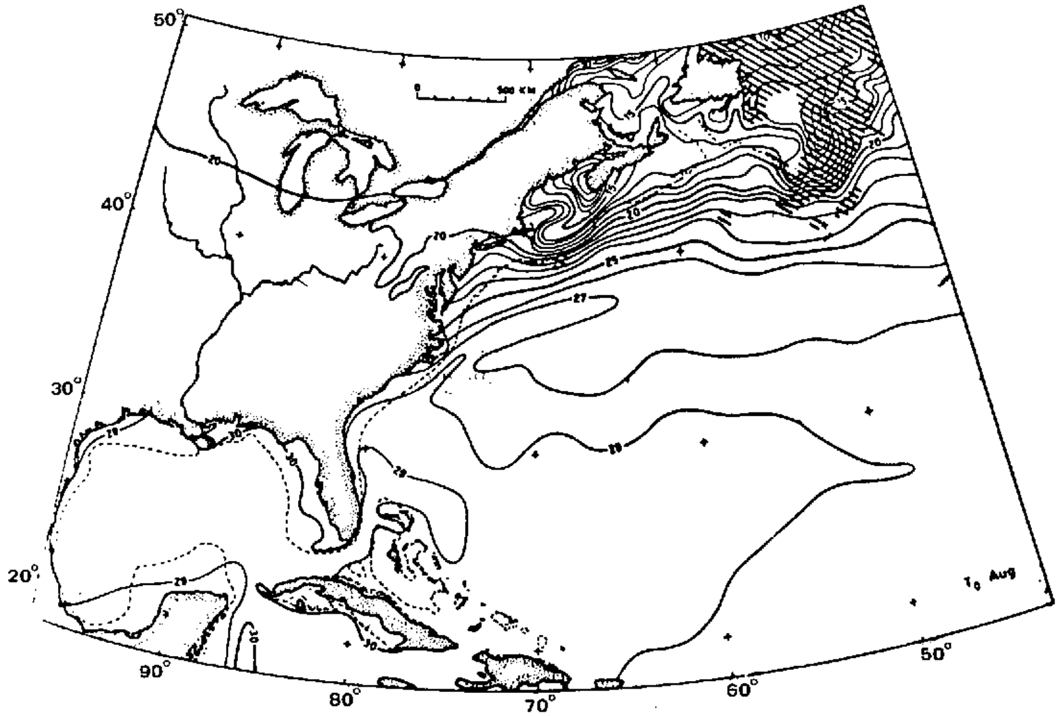

Figure 13. Surface Temperature of Western North Atlantic Ocean During August. Based on unpublished data of 1940 to 1970 in files of Woods Hole Oceanographic Institution: 18,500 observations within about 200 km of shore and 19,400 observations farther at sea. Isotherms on land and areas of iceberg and heavy-sea-ice sightings as for Figure 12.[29]

Therefore it is reasonable to recommend the Miami site as the prime mainland U.S. offshore SSPP site. The various tropical sites are better for the purposes of demonstrating SSPP concepts and feasabilities than the Miami site.

At this point the prime sites for SSPP construction need not be gone into in detail. It is recommended that the prime sites for SSPP construction be:

- Puerto Rico (south coast)
- St. Croix, U.S. Virgin Islands (north coast)
- Hawaiian Islands (various sites)
- The various U.S. Pacific Islands (Micronesia): Largest sea thermal resource in the world - 5,000,000 square miles
- Miami, Florida

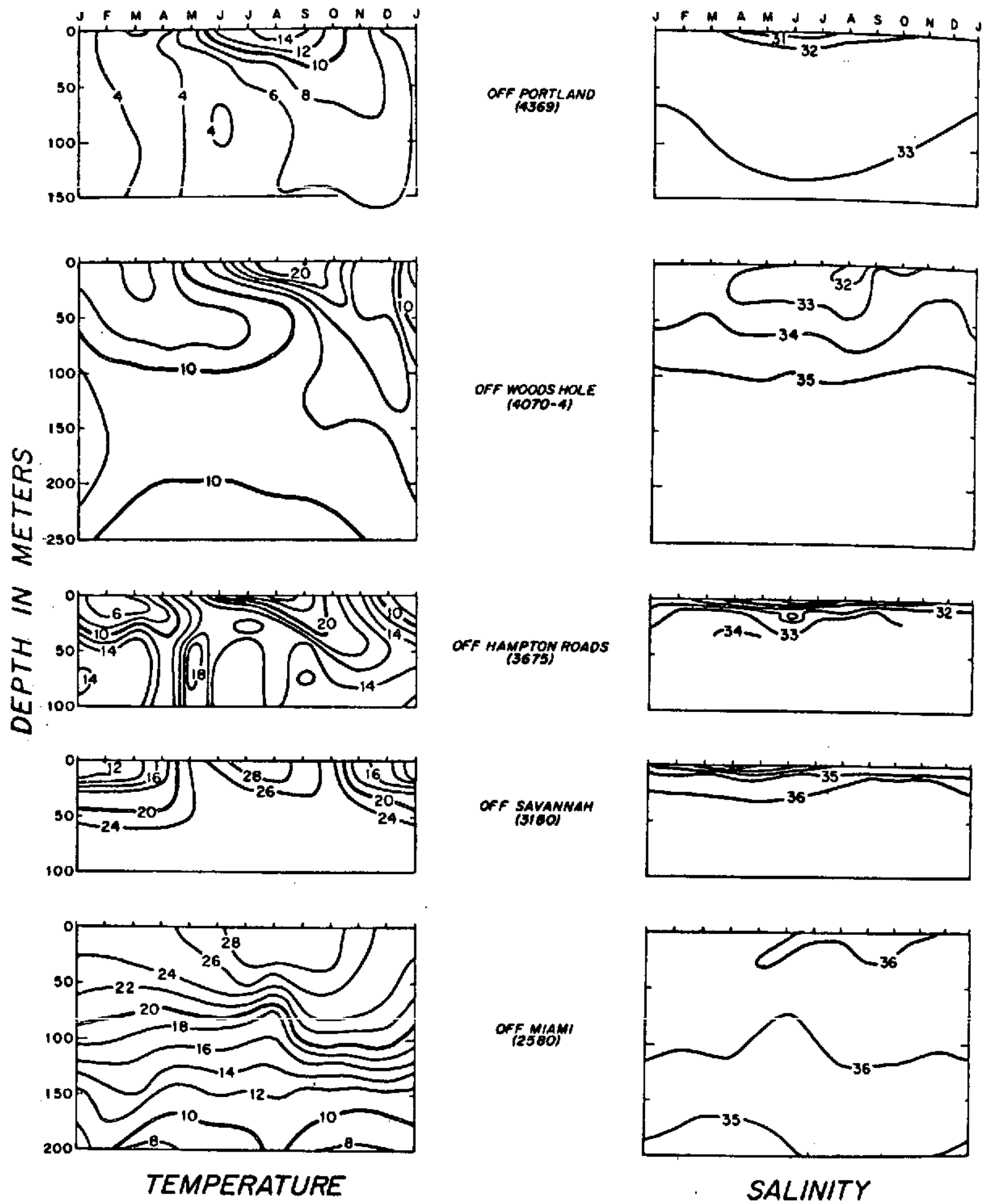

Figure 14. Average Annual Variation of Temperature and Salinity at Depth in Five Selected Areas on Atlantic Continental Shelf. Four-digit numbers indicate 1° quadrangles; for example, notation (4369) off Portland denotes area between 43° and 44° lat. and between 69° and 70° long. Based upon unpublished data in files of Woods Hole Oceanographic Institution.[29]

In addition, there are numerous foreign sites; many in areas lacking electric power and fresh water. Any successful U.S. SSPP would tend to generate great demand by various nations for SSPP technology. The potential payoff here is great. The word "great" is used not only because of the SSPP's power potential, but also because of the SSPP's food and fresh water production capabilities. The food producing capabilities of the SSPP will be discussed. The fresh water production capabilities will be gone into in the open cycle SSPP discussion below.

The discussion of the artificial upwelling induced by the cold water pumping is gone into in References 31, 32, and 33. There is no need to go into the increasing need for food worldwide at this time and the projected increased need for food due to increasing population in the next few decades. We have recently witnessed famine conditions in Central Africa, South America, India, Bangladesh, Burma, and in other localities. The SSPP concept offers, in addition to its power production capabilities, the gift of mariculture. One may define mariculture, for our purposes, to be synonomous with ocean farming. Mussel farming has proved very successful in Spain and the Japanese have large oyster culture operations. The farming of shrimp is becoming commonplace and fish have been raised for centuries. The selection of breeding stock for mariculture is a well established science.

For an adequate period of time an algae growth plant (farm) was proved successful.[34] Algae (chlorella pyrenoidosa) growth rates of 14.4g of dry algae per square meter per day were achieved. In this experiment a nutrient medium was used. The nutrient medium associated with the SSPP is the ocean itself. Deep ocean water (the cold water used for condensing purposes) is many times richer than surface water in nitrates, phosphates and silicates, which are essential nutrients for phytoplankton growth.

One can route the SSPP condenser (nutrient rich) water into lagoons, tanks or ponds where it will stimulate the photosynthetic process by providing the necessary nutrients. The phytoplankton concentration in the mariculture system may then be used to obtain optimum yields of shellfish, shrimp larvae, filter feeding fish, etc. Efficiencies of 70% have been obtained for Euphausia Pacifica feeding on Dunaliella. Efficiencies of 55% for brime shrimp, Artemia, feeding on Dunaliella have been obtained. However, assume only a 10% rate of phytoplankton conversion to a secondary producer. This 10% conversion operating on a single acre would yield 20 tons of secondary producer per year. Note that mariculture can also be accomplished in the open sea by the artificial SSPP upwelling system.

Roels et al.[32] chose a site 1.6km offshore from St. Croix where a 1000 meter ocean depth was found to occur. They found that the deep water, in addition to its nutritious values, was free of human disease producing organisms, shellfish parasites, predators, fouling organisms and man-made pollutants. They pumped this water onshore and grew clams, oysters and scallops to market size in a year.

The financial rewards from a mariculture system can be greater than that that can be realized by the sale of power. The mariculture system is exceedingly desirable, but there remain two major areas of concern.

- How will a new large source of nutritious water affect the ocean ecology of a given area? One may not assume that because one has greater growth of algae, shellfish, fish, etc. the effects are beneficial. This should be studied in a pilot SSPP and natural upwelling areas should be studied more closely.

- International law must allow for the harvesting of the SSPP's mariculture products in international waters without interference by others. Security may also be a problem. A method of obtaining fees from fishing vessels operating in the SSPP upwelling area should be legislated internationally.

V. MATERIALS

Instead of going into the advantages and disadvantages of various materials for SSPP construction (hull, cold water pipe, heat exchanger housing, etc.) let us state from the start that a complete evaluation of over a dozen potential structural materials for SSPP use has been made. In this study structural strength, corrosion resistance, manufacturing and assembly difficulties, initial cost and maintenance costs were taken into consideration and the decision process determined concrete to be the best choice for SSPP construction (at any ocean depth above the thermocline). Therefore let us only describe some of the advantages and properties of concrete and the reasons concrete is appropriate for SSPP use.[35]

The Romans were among the first to use concrete in a marine environment over 2000 years ago.[36] In fact the first century concrete pillars erected in the Bay of Pozzuoli are still serviceable after 1900 years underwater. It is doubtful if any metal could have withstood the corrosive action of the sea for this length of time. The first reinforced concrete structure for maritime use was built in Southampton, England in 1899 and was in service and in excellent condition in 1955. However, the 1928-9 precast concrete used in the San Mateo-Hayward Bridge (San Francisco Bay) required extensive repairs to the corroded reinforcement. This experience tends to rule out the use of high porosity concrete in marine environments.

Many floating concrete structures have been successful. The first were Lambot's (1848) 10 foot reinforced mortar rowboats, one of which was afloat more than a century later. Nervi in 1946 built the ferro-cement vessel, Irene, which displaced 165 tons and had a hull almost 1.5 inches thick. After eight years of ocean service the Irene needed no maintenance. The 2500 ton concrete ship Armistice, built in England in 1919, survived until scuttled in 1969. It is estimated that concrete vessels displacing 500,000 tons have been built.[37] The disadvantage of these vessels was that reinforced concrete hulls were heavier than the comparatively thin steel hulls and cargo carrying capacity is one of the crucial parameters in ship design.

The structure closest to the SSPP that has been constructed is the Ekofisk. The Ekofisk is a prestressed concrete oil storage and tanker-loading caisson built in 1971-72 in Stavanger, Norway.[38] It displaced 215,000 tons floating. It was towed into position - as the SSPP will have to be - in the North Sea and then ballasted with sea water until it rested on the sea bed in 70 meters of water. Once in position, the caisson was anchored by its own weight plus the weight of its contents with no additional anchorage. This concept applies to the SSPP anchoring system as well as the SSPP itself. In the Ekofisk situation both steel and concrete alternatives were proposed. Concrete was adopted for cost and operational reasons.

One can find in Gerwick[39] the significant properties of concrete in an ocean environment that apply to SSPPs and maintenance. There are beneficial effects associated with submerging concrete. Generally, concrete submerged in sea water continues to cure and increases its strength in time. The underwater environment is conducive to optimal curing because the hydration water is trapped in the concrete and any heat generated by the reaction is conducted away. Shrinkage due to drying will not occur in the underwater environment. There are also no significant temperature changes experienced by the concrete.

One must still worry about permability. The effects of pressure on curing must be taken into consideration for the cold water pipe (depths on the order of 1,000 meters) but not for SSPP structure. This tends to be a significant fact to be overcome in designing concrete cold water pipes. This is because it is not advisable to place the SSPP below (or much below) the thermocline and it has been shown that concrete cured in 200 feet of water is dense and strong. However, it has been shown that concrete cured at 600 feet has less strength.[40] Marine organisms will be a problem adding weight, changing friction coefficients, and reducing strength by boring. It is not practical to try to design the concrete resistant to biofouling; one can live with it on the structure with insignificant loss in any of the desired structural and dynamic properties.

The problem of the cold water pipe will be considered later and the type of material adequate for its construction will be analyzed.

VI. THE NITINOL ALTERNATIVE

Prior to discussing heat exchangers, turbines, working fluids, etc., we will delve into a viable alternative to the "evaporator-condenser" SSPP process: the Nitinol engine.

Figure 15 adequately describes the qualitative features of Nitinol-55. (1) The material can be obtained in practically any shape desired, then (2) the material is deformed into the configuration one desires the material to remember for all time. (3) This "historical" shape is then clamped in a fixture that constrains the memory configuration. (4) The Nitinol is then heated (this fixes the deformation history in the material) and (5) cooled. The material can now be deformed into its "working" shape, or some intermediate shape. The material upon being heated to its recovery temperature will return to its historical shape. This process can be repeated many times - up to millions of cycles. When Nitinol is heated and induced to return to its historical shape it exerts considerable force and can do significant mechanical work. It is this property that allows one to design an SSPP Nitinol engine. Figure 16 shows that the recovery at the 6% constant strain level is practically constant and does not fall off significantly after many cycles.

One of the advantages of Nitinol for SSPP applications is that it is not susceptible to stress corrosion in sea water.[42] The corrosion resistance of Nitinol in stagnant sea water has not been determined with certainty.

A Nitinol engine with certain characteristics applicable to SSPP's has been patented.[43] Figure 17 illustrates the basic principles involved in the design. A strip of Nitinol is deflected, at the subsurface (cold) water temperature in the SSPP, by an amount Z by a weight W_1. A second weight W_2 is added after the maximum deflection Z is attained. The SSPP surface water (warm) then is brought in to flow over the Nitinol.

The temperature of the surface water is sufficient to exceed the Nitinol transition range temperature and return the Nitinol to its zero-deflection or historical configuration. The amount of useful work performed ($W_1 Z + W_2 Z$) is greater than the work used to deform the Nitinol initially ($W_1 Z$). Thus the Nitinol strip has converted the thermal energy of the ocean into mechanical energy which can then be converted into electrical energy by standard procedures. The fatigue strength of Nitinol is high both in the pre- and post-transition temperature ranges and as shown in Figure 16, there is no significant decay in percent recovery with increasing cycles. The data also indicates that one should not use strains above 8% insofar as this strain appears to be in the vicinity of the maximum recovery stress and work. Efficiencies of 25% have been obtained and it is hoped that SSPP Nitinol can be designed to operate appropriately and highly efficiently at temperature differences one observes at the prime SSPP sites.

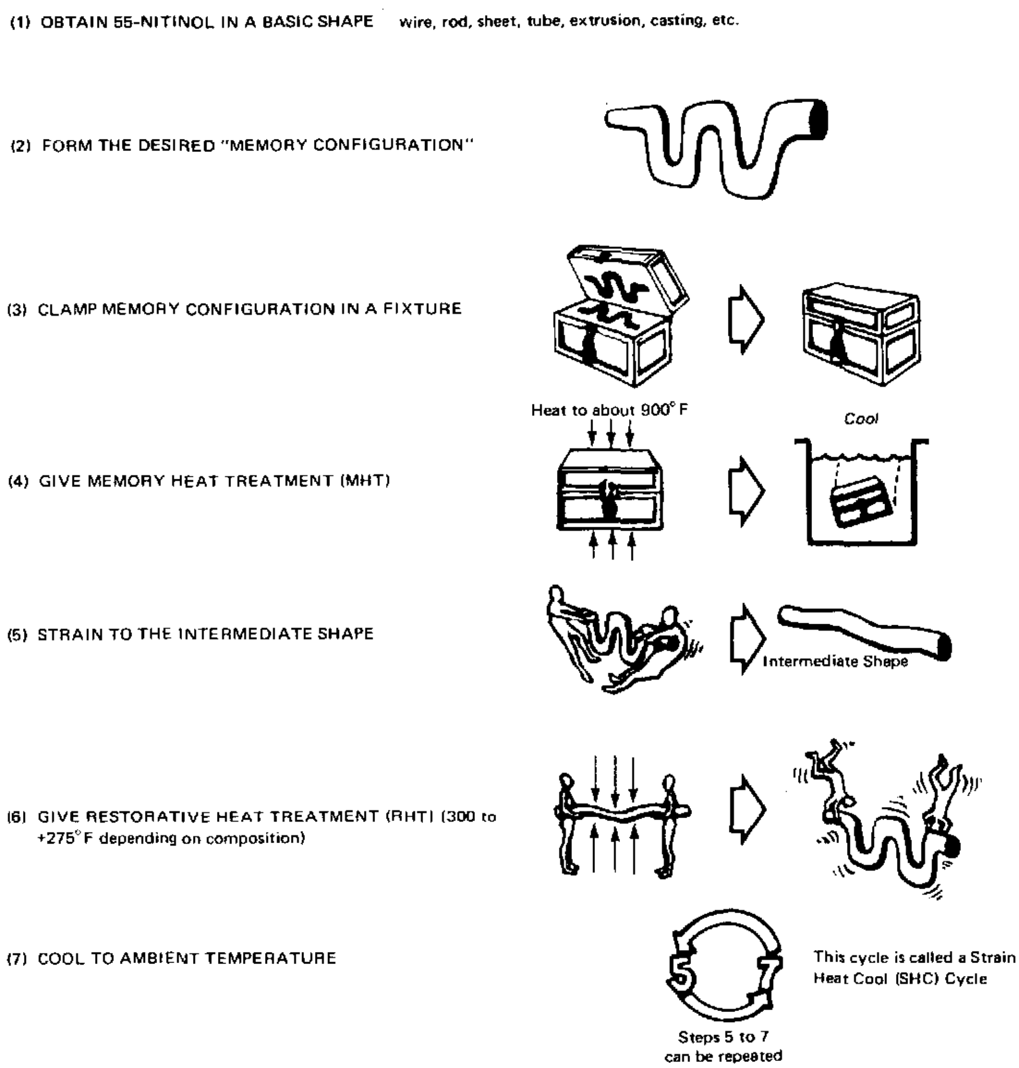

Figure 15. The Nitinol Deformation-Memory Process

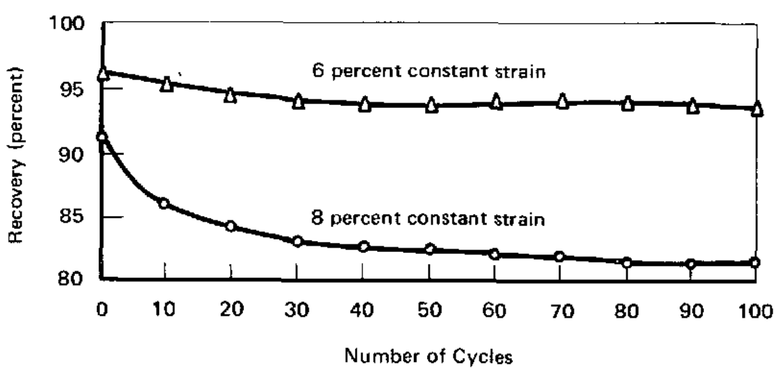

Figure 16. Shape Recovery Fatigue Curve for 0.20 in. Diameter Nitinol Wire

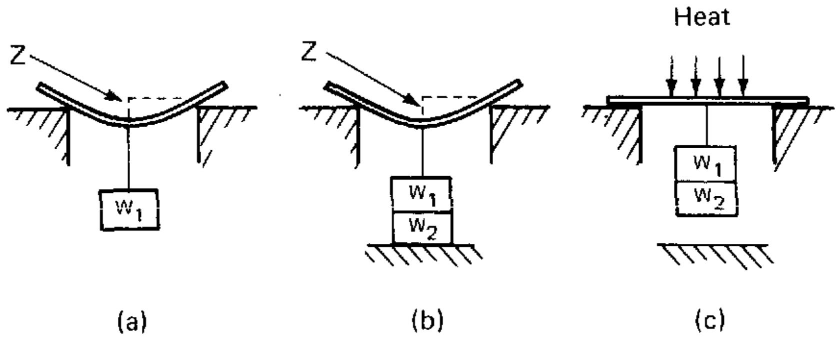

Figure 17. Schematic Diagram Illustrating the Conversion of Heat Energy to Mechanical Energy Using 55-Nitinol

More research and development work must be done to perfect a Nitinol engine for SSPP applications, but the work that must be done to perfect heat exchangers, turbines and the peripheral equipment for a closed cycle SSPP is an order of magnitude greater than for the equivalent Nitinol development. From preliminary calculations it appears that Nitinol engines will cost less than the equivalent closed cycle systems proposed, however, an adequate system design must be performed prior to an unequivocal statement of this nature. To summarize the Nitinol engine SSPP is a viable concept. It offers some important advantages over some closed cycle SSPP designs, however, it has not been proven in the hardware sense. It is recommended that any decision to proceed with the closed cycle SSPP concept should proceed concurrently with research into the area of the Nitinol SSPP alternative.

VII. THE SSPP AND THE CLAUDE CYCLE

One reading the popular scientific literature, concerning the various proposals for the SSPP, inevitably comes across statements to the effect that the Claude process is not workable or it is inefficient and that an open cycle system is not even to be seriously considered when compared to closed cycle SSPP designs. When one attempts to do some detective work and track down the source of these statements in the scientific and technical literature one finds more of the same types of statements. There are, indeed, serious technological difficulties involved in an open cycle SSPP design, but these difficulties may be orders of magnitude smaller than those difficulties associated with closed cycle SSPP designs.

It must be pointed out that the first SSPP proposals were tied to the closed cycle. The closed cycle advocates were the Frenchman D'Arsonval, the American

Campbell and the Italians Dornig and Boggia. Claude was early to recognize certain deficiencies in their ideas:[7]

> "The inventors referred to proposed a means, namely, the use of liquified gases, vaporized under pressure by the tepid surface water, and then condensed by the cold water after their expansion in a motor. Manifestly such a solution is burdened by a number of inconveniences, one of them being the high cost of such evanescent substances, and another the necessity of transmitting enormous quantities of heat through the inevitably dirty walls of immense boilers with such a small difference of temperature."

These words are as applicable to the closed cycle SSPP concept today as they were in 1930 when they were written. The closed cycle technology of the year 1930 was relatively advanced. In fact many of the fossil fuel power plants in our major cities were built before 1930 and are still in operation today.

Recall that Claude successfully demonstrated the open cycle with a 60 kw SSPP at Dugrée, Belgium. A 20°C ΔT created enough steam to run a turbine with a one meter diameter wheel at 5,000 rpm. At his Cuban plant Claude used a 14°C ΔT to generate 22 kw of electric power. The pressure in the boiler was 23 mm at 25°C and the pressure in the condenser was 16 mm at 15°C. Claude also showed that the efficiency of an SSPP increased as $(\Delta T)^2$. Thus the importance of obtaining the largest temperature difference possible.

The objection to the open cycle on the basis that the pressures generated by the steam are so small so as to be useless is the primary objection presented by the open cycle detractors. Claude was also stung by this criticism and stated:

> "However, we had hardly uttered our proposition before protestations and objections fell on our heads like hail. First of all, so extremely low is the pressure of such steam that everyone doubted that it could be utilized; and it is strange, indeed, that no one had conceived of its possibilities prior to the very deviser of processes employing the highest pressures ever used in industry . . ."

Figure 7 is a schematic of an open cycle SSPP. This type of plant has its basis in the fact that one can lower the temperature water boils at by lowering the pressure upon it. Thus in Figure 7 the tepid ocean surface water will boil in the flash evaporator because the air has been evacuated from the chamber causing a partial vacuum in it. The steam generated thereby spins the turbine. The steam is then condensed via the cold deep ocean water. This condensed steam is pure (desalinated) water and constitutes one of the truly significant advantages of the open cycle over the closed cycle.

Davitian and McLean[44] object to the Claude cycle on the basis that the SSPP vapor pressure of only 25-30 mm-Hg would require very large turbines. They estimate that for a one million kilowatt plant a football field size nozzle throat would be required. Othmer and Roels attempt to answer this and other objections.[45] It is perhaps unreasonable to build a one gigawatt SSPP with its 10,000 m^2 nozzle throat. A series of 10 megawatt SSPPs may be preferable to one very large SSPP. Even though the turbines for the open cycle SSPP are relatively large the pressures and temperatures under which they must operate are relatively small. Thus these turbines can be made of lightweight materials such as plastics, fiberglass, composites, etc. It may be cheaper to build large plastic turbines than to build the relatively smaller, but stronger, closed cycle turbines.

The open cycle SSPP has the potential to produce up to 25% more power than the closed cycle SSPP. The reason for this is that there is no loss in temperature in the exchange of heat from the tepid surface water to the working fluid in the open cycle process. Also in the closed cycle SSPP the heat exchangers are the most expensive component of the plant. This cost is saved if the Claude process is used. Moreover, one need not contemplate the loss of volatile or hazardous working fluids in the open cycle.

Closed cycle systems are extremely sensitive to biofouling of the heat exchangers. This problem may severely limit the life of any closed cycle SSPP. Since boiling in the open cycle SSPP is primarily dependent upon the vacuum and not the temperature of heat transfer surfaces the biofouling constraint does not approach the criticality it does with the closed cycle case. If biofouling is the factor that most severely limits SSPP life, an open cycle SSPP would survive a great deal longer than a closed cycle plant. Even the Nitinol engine will be susceptible to biofouling and the formation of slime on the surface of the material which progressively cuts down on the transfer of heat from the tepid (and cold) water to the material will drastically cut down on its efficiency.

An equally convincing reason for building SSPPs with open cycle power generators was adequately described by Barnea.[46] All SSPP designs make use of massive amounts of cold deep ocean water, therefore no one design possesses any significant advantage over any other with respect to mariculture considerations. However, the Claude cycle SSPP is the only system under consideration that produces fresh water as a byproduct. The United Nations does not foresee any long term energy shortages, but predicts serious water shortages.

Othmer and Roels state[47] "if the cost of producing power is taken as 6 mills per kilowatt hour, fresh water costs are $1.38 per thousand gallons; or if power cost is taken as one cent per kilowatt hour, then fresh water costs $1.28 per thousand gallons." Thus a small SSPP built with off-the-shelf hardware could produce power at a cost of one cent per kilowatt-hour. But consider now the fact that many islands which are prime SSPP sites have shortages of water. Also many countries with prime SSPP sites are largely desert and the water desalinated by a Claude cycle SSPP may be more valuable than the power produced. Even at the Miami site there are fresh water problems due to incessant pumping and use of the subsurface water. The aquifer level has been dangerously lowered and salt water intrusion into the aquifer is becoming a serious problem. A new fresh water source would be very welcome there.

In any case the value of the distilled and desalinated water produced in the SSPP by condensing the steam should be several times the value of the power produced.[45]

To summarize, the Claude (or open) cycle SSPP is the most attractive concept that has yet appeared. It offers the following advantages:

(a) No loss in temperature due to the use of heat exchangers (increased power production)

(b) No need for expensive heat exchangers

(c) The production of desalinated and distilled water

(d) Relative immunity to biological fouling of surfaces

(e) Inexpensive turbines required

(f) Claude cycle SSPP technology will create the greatest demand for SSPPs by many nations due to (c) above.

It is therefore recommended that the Claude cycle SSPP be given first priority for research, development and construction.

It does not appear to be reasonable to put "all our eggs" in the closed cycle basket given the heat exchanger, biofouling, etc. problems associated with that system.

VIII. THE CLOSED CYCLE SSPP

Figures 3, 4, 5, 6 and 8 illustrate the basic principles of the closed cycle SSPP operation and some of the variations that have been proposed. These SSPPs have been discussed to some extent in Section III. Most of the research done in the past few years has been associated with the closed cycle SSPP. Therefore in this section the various components of the closed cycle SSPP design will be analyzed even though these components can be used in the Claude or Nitinol designs with little or no modification. This also presents the opportunity to review the technical problems associated with SSPP designs in general. Let us begin with the most difficult problem first. The problem is both economic and technical and is associated with the closed cycle SSPP only.

A. Heat Exchangers

Anderson[48,49] and others have accurately observed that the greatest economic problem in the construction of a closed cycle SSPP is the construction of low cost heat exchangers. The greatest technological problem in closed cycle SSPP design is to design and build heat exchangers that transmit approximately 30 times as much heat per kilowatt as is now being done by the heat exchangers in typical fossil fuel power plants. Moreover one must perform this feat while making use of much smaller temperature differences than those at which conventional power plants make use of in their operation. The small ΔT and the need for very high efficiency dictate to the SSPP designer that he must design massively large heat exchangers. Now since the heat exchangers will necessarily be large, one must find a way to keep the cost down and then insure long lifetimes for the heat exchangers so as to make the SSPP investment attractive.

The Carnegie-Mellon University heat exchanger design consists of hexagonally nested 10 ft pipes, one inch in diameter, through which the tepid surface water is pumped and the working fluid, which flows around the pipes, is consequently boiled. On the water side of the tubes, the tepid water flows with a velocity of 8 ft/sec. The temperature losses that are intrinsic properties of this heat exchanger design are the following: a loss of 4°C through the 3 mil film, a 2°C loss through the aluminum tube wall, and another 4°C loss through the 3 mil film on the working fluid side with working fluid having been imparted a velocity of 8 ft/sec. This adds up to a total loss of 10°C due to the heat exchanger operation. Since one has only a ΔT of the order of 20°C, one half of the available ΔT is dissipated by the heat exchanger's operation.

The CMU design also incorporates 25 mil depth flutes on the outside, or working fluid side of the heat exchanger pipes. It should be noted that flutes on the tepid water side of the heat exchanger or on the cold water side of the heat exchanger (condenser) would create near optimum sites for biological growth due to the tendency of the flutes to induce local turbulence.

The UMASS SSPP heat exchanger is of the plate and fin type make of Cu Ni in a 90 to 10 ratio. Plastic was also considered as a heat exchanger material because of its low cost, as was aluminum. Cu Ni was chosen in spite of its high cost because of its alleged anti-biofouling properties.

A mathematical model that characterizes the SSPP evaporator, turbine and condenser has been developed at the University of Massachusetts. Let us now consider some of the results of their simulation.

The first result indicates that compact heat exchangers of a plate-fin design with extended interior exchange surfaces are superior to plain tube and shell exchangers. The second result is that they could not determine the optimum plate-fin heat exchanger design. Small diameter tubes appear to offer advantages over larger tubes, however, one must take the possibility of clogging into consideration and also the difficulty involved in manufacturing small diameter tubes. Figure 18 graphically illustrates some of the above mentioned results. Contrary to the CMU experience the UMASS study indicates that none of the current enhancement techniques will succeed in raising the heat transfer efficiency over that obtained with internally extended surfaces.

It appears that the UMASS system considers the problem of biofouling of the heat exchanger external surfaces a bit more seriously than the CMU designs consider it to be. In Reference 17 recognition is given to the fact that exposing the heat exchanger surfaces to sea water causes those surfaces to become covered by a thin film of microbial growth that will essentially greatly reduce the efficiency of the boiler and condenser. However, they quote a 1948 paper[51] and dismiss the problem. The results in Reference 51 indicate that one part in four million of clovine is sufficient to prevent microbial growth. It's doubtful that the results in Reference 51 apply to the heat exchanger situation in an SSPP with its massive flows of water and continuously distributed points of localized turbulence. To the UMASS people[21] biofouling remains an unresolved problem. They quote References 52 and 53 to back up their statement. They present three basic biofouling prevention methods (to be applied in light or dark situations).

- Move the tepid water past the boilers with a velocity greater than 2.2 knots[54]
- Use CuNi to construct the heat exchangers to prevent biofouling[55]
- Continuous wetting of the heat exchanger surfaces with a sodium hypochlorite solution[50]

Thus both groups have adopted the philosophy that the biofouling problem can be easily solved and it is only the economics of the solution that gives any cause for concern. Little concern is given to the fact that one must pump on the order of 5,000,000 gal/min of tepid water past the boilers and about twice that, or 10,000,000 gal/min, of nutritious cold bottom water past the condensers which will warm it up a bit. Moreover, the creation of an artificial upwelling zone surrounding the SSPP implies that even the tepid water will be saturated with

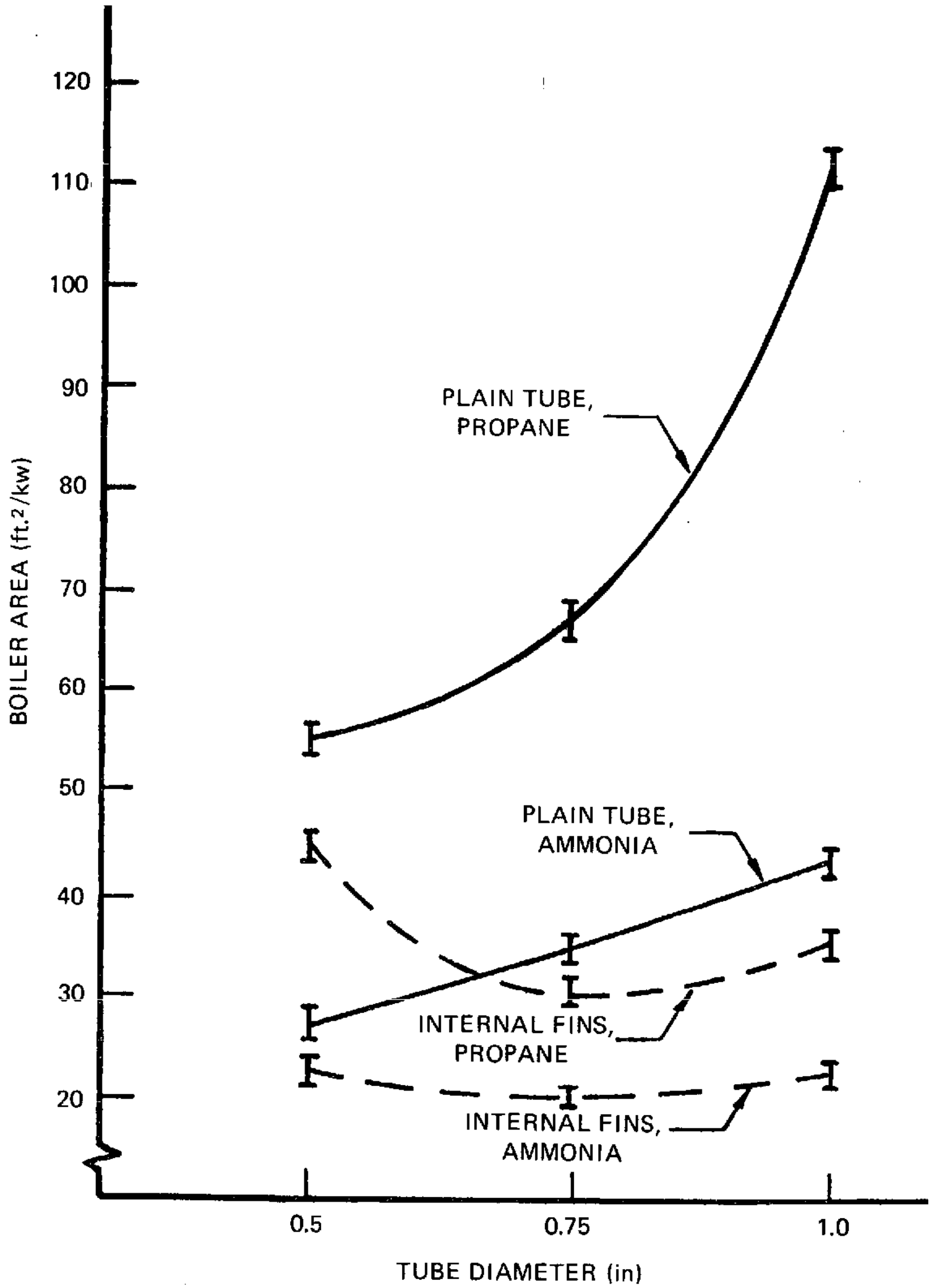

Figure 18. UMASS Heat Exchanger Study Results

nutrients conducive to biological growth and, indeed, this water will have an increased number of organisms that are potentially detrimental to SSPP heat exchanger heat conduction properties.

It is evident that biofouling is the most serious problem associated with heat exchanger design especially because of the small ΔT available and the high efficiency that the SSPP must operate at to be classified as successful. The projected lifetimes of the SSPP heat exchangers are 25 years for the CMU design and 40 years for the UMASS design. None of the methods proposed for biofouling prevention can be successful in an open system for any length of time. Consider the wide range of conditions under which life can sustain and reproduce itself. Organisms can grow in acidic and basic solutions. Organisms grow in very cold regions; Antartica, and in very hot regions; hot water pools in Yellowstone National Park. They have also been observed flourishing in nuclear reactors constantly being irradiated by many thousands of times the radiation dose that would quickly be fatal to humans. Life exists at very low pressures and very high pressures from top of Mount Everest to the bottom of the oceans and in the deepest mines. Indeed, it is these facts that form part of the basis for NASA's Viking mission - to land an automated scientific payload on the surface of Mars.[57,58] The reasoning being that if life can exist on earth under the most extreme conditions there is a good possibility that life exists on Mars. Thus far one basic principle has emerged in the study of life under extreme conditions: where there is water there is life. And where there is an SSPP there is a lot of water. Note that it does not take very much biological growth mass to destroy an SSPP heat exchanger's heat transfer characteristics. To design against this sort of contamination, in an environment where one is constantly recirculating massive quantities of sea water, one might have to use a non-trivial amount of the power produced by the SSPP, or design somewhat expensive antifouling subsystems, or replace the heat exchangers as they become fouled (throw aways), or use expensive materials, or use chemical retardants, or use some combination of the above five panaceae.

It is very difficult to use the existing data on biofouling. This data was obtained for ships, pipes, offshore structures and at best large ΔT power plants or engines. It makes little difference if there is a microscopic layer of biological growth on, say, the interior of a water pipe or an SSPP cold water pipe - it might even improve its flow characteristics. However, this same microscopic layer can be catastrophic to the efficient operation of an SSPP heat exchanger.

Before any consideration is given to the construction of a closed cycle SSPP it is recommended that the biofouling problem be thoroughly studied by means of basic experiments and the testing of models of SSPP heat exchangers with various materials and different methods of preventing biofouling. Data must be obtained on the degradation of heat transfer characteristics with time in the ocean environment at the prime SSPP sites.

Corrosion, stress corrosion and to a lesser extent corrosion fatigue and material aging are likely to present some difficulties in the design of the heat exchangers.[59,60] The corrosion problems are not serious in that one can design corrosion resistant structures and components. In the heat exchanger situation one must optimize heat transfer characteristics in conjunction with optimizing anti-corrosion properties. If one performs this optimization with cost as a constraint it may turn out to be a somewhat difficult chore with some difficult trade-offs taking the designed lifetime of the SSPP as another constraint.

In addition to the choice of material there are other means available to augment heat transfer.[50,61] One attractive technique has been proposed by Young,[62] and Young and Hummell.[63] Spots of teflon or other nonwetting material on the heated surface promote nucleations as shown in Figure 19.

There are many other techniques to augment heat transfer (see Ref. 50 for example), however, most use up more energy than they add by their augmentation.

An interesting alternative SSPP heat exchanger has been proposed by Strauss.[64] This alternative involves applying the concepts of heat pipes and thermosyphons in the heat exchanger design. The basic concepts of the functioning of heat pipes and thermosyphons can be found in References 65 through 70. Heat pipes and thermosyphons are both sealed objects, commonly cylindrically shaped, containing a fluid present predominately as a vapor. This fluid is at the saturation temperature corresponding to the vapor pressure.

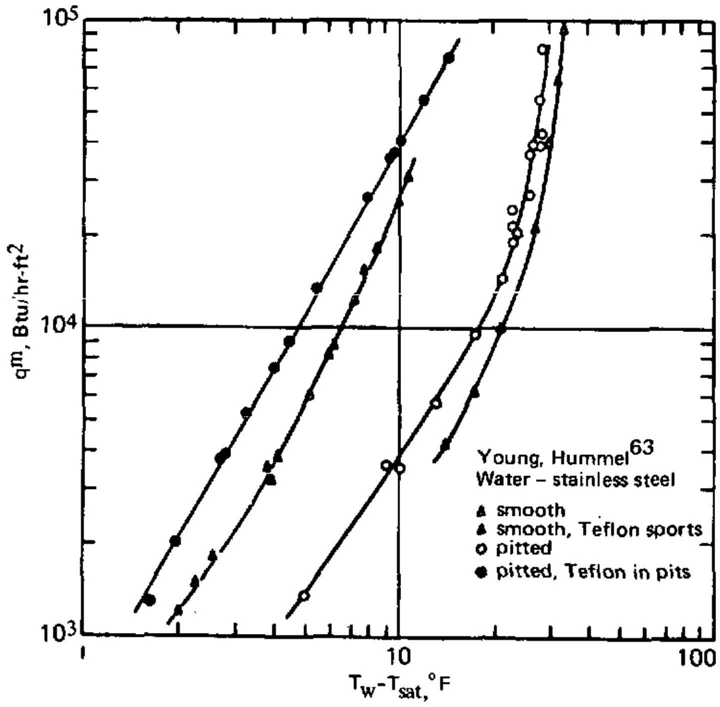

Figure 19. Influence of Surface Treatment on Saturated Pool Boiling

The thermosyphon is a vertical device that transfers heat from below the device, boiling the fluid and raising the internal pressure and temperature. To move towards equilibrium heat must be transferred from the top portion of the thermosyphon. This condenses the vapor at the top and the liquid returns under gravity to the evaporation portion of the thermosyphon.

The heat pipe is a thermosyphon wherein the condensate flows under the action of capillary forces, rather than under the action of gravitational forces as in the thermosyphon. In designing an SSPP heat exchanger one may make use of both gravity and capillarity.

In practice the heat pipe is simply a tube or duct whose wall is clad with a layer of porous material, usually called the wick, as shown in Figure 20. Since both evaporation and condensation can occur at almost the same temperature, the total temperature drop over a heat pipe may be very small, a few degrees or so, as in SSPP applications, whereas the heat transported may be of the order of kilowatts. The effective thermal conductance can, therefore, be more than tens of thousands of times that of a copper rod of the same size. Add the assistance of gravity and one has a truly marvelous heat transfer device. Figure 21 illustrates the method of obtaining an optimally designed heat pipe.

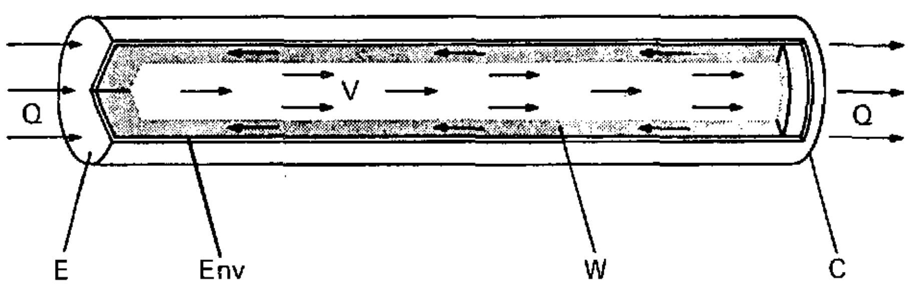

Figure 20. Simple Cylindrical Heat Pipe. The wall Env of the completely sealed pipe is clad on the inside with a porous layer W, the 'wick'. The heat entering the left-hand end of the pipe, the 'evaporator' E, causes fluid in the wick to evaporate. Latent heat is thus taken up by the vapor, and the vapor pressure at that end rises slightly. The vapor flows from the evaporator through the vapor duct V to the condenser C, where the latent heat is released upon condensation. The condensate is then recycled through the wick to the evaporator. In addition to the locations of the evaporator and the condenser — which need not be restricted to the end — the pipe is provided with external heat insulation. Q input and output heat flux.[69]

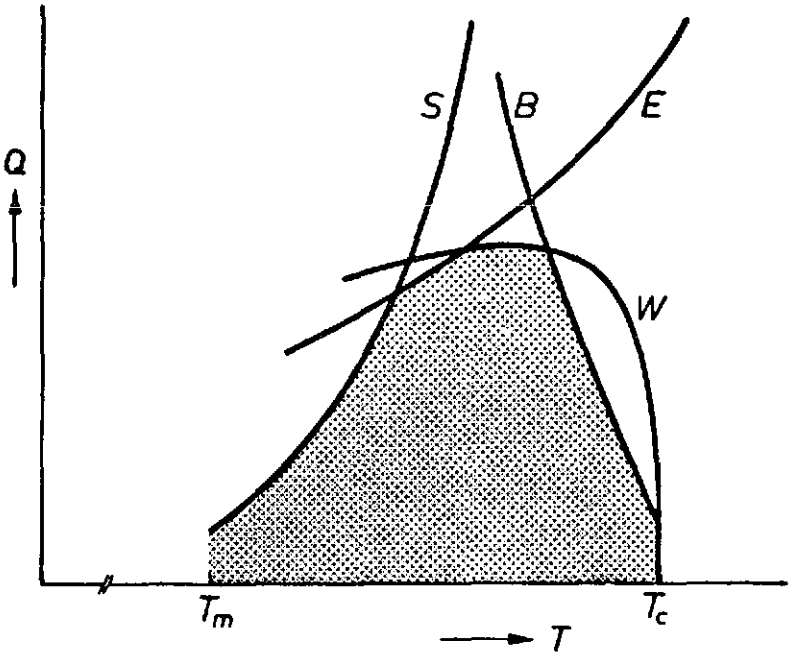

Figure 21. The Working Range of a Heat Pipe. The axial heat flux Q is shown as a function of the temperature T. The heat pipe operates in the shaded area. The limits of T are the melting point T_m and the critical point T_c of the working medium. The upper limits of the heat transport in a heat pipe are determined in the first place by the velocity of sound in the vapor (curve S), and at higher operating temperatures by the maximum liquid-flow rate which the wick is capable of handling (curve W). Other limitations are due to the take-up of liquid from the wick by the vapor flow (curve E) and boiling of the fluid in the wick (curve B).[69]

In the SSPP heat exchanger situation the heat-transport capability is moderate and perhaps it offers no advantage over other heat exchanger suggestions, Figure 22. The heat transport capability of a heat pipe is due in large part to the fact that the thermal resistance of the vapor duct is very small. The heat flux is limited by the heat transfer into and out of the pipe and the evaporation and condensation processes. One advantage of the heat pipe is that it is a reversible unit. Thermal energy may be transferred through heat pipes from either section to the other section. Thus one may use ammonia as a cleaning (and toxic) agent as well as a working fluid simply by mechanically reversing the heat exchangers. This type of design is likely to be expensive and seals will have to be designed. In addition the use of heat pipes or thermosyphons result in the construction of larger heat exchanger units.

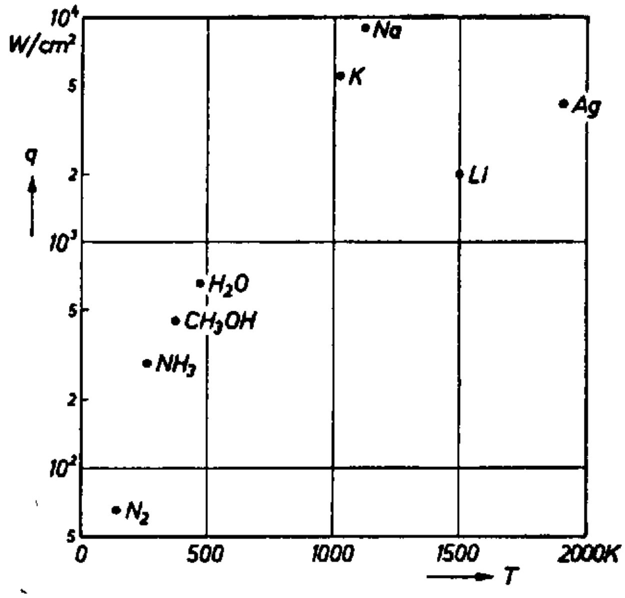

Figure 22. Diagram of the Measured Maximum Heat Flux q for Various Working Fluids, and the Temperature at which these are Ordinarily Used. A higher operating temperature corresponds in general to a higher heat-transport capability.[69]

Thus no matter which way one turns the heat exchangers present a significant technical problem that may not have an economic solution within the given constraints. This is one major reason for the great attractiveness of the Claude (open) cycle and the relative attractiveness of the Nitinol engine when compared to closed cycle concept.

Once the basic heat exchanger concepts have been decided upon one must select a working fluid and then optimize the heat exchanger-working fluid combination. This task is not simply one of choosing the fluid with the best thermodynamic properties as will be seen immediately below.

B. Working Fluids

The major contenders for the working fluid job are: (a) ammonia, favored by the CMU group; (b) propane, favored by the UMASS group; (c) the halo-carbon R-12/31, favored by J. H. Anderson; and (d) R-114, favored by the Japanese (see Table 8 from Reference 25). All of candidates yield cycle efficiencies near the same theoretical maximum. Table 9 illustrates some of the UMASS results on working fluids[21] (also, see Tables 2 and 3).

The working fluid should be optimized with respect to the heat exchangers and not the turbines, as the heat exchangers are the critical components in the SSPP design and one knows how to optimize turbine operation for (almost) any working fluid.

Table 8

Evaluation of SSPPs using Various Working Fluids

Items \ Working Fluid	R11	R12	R13	R21	R22	R113	R114	NH_3	C_2H_6	C_3H_8	C_2H_4	Water
Adiabatic Enthalpy Drop	2 Kcal/kg	2.2	1.1	3.5	1.9	2.8	3.1	8.0	3.0	5.0	2.0	7.2
Turbine Inlet Flow	56.4 m^3/s	80.3	2.39	21.5	8.5	5.6	11.5	13.7	2.63	6.02	1.51	3.760
Turbine Inlet Pressure	0.985 ata	6.19	32.3	2.0	9.5	0.50	2.4	7.59	39.0	9.63	67.9	0.0363
Turbine Exhaust Pressure	0.557	4.08	23.9	1.10	6.61	0.25	1.3	58.0	30.3	6.12	51.0	0.0125
Turbine Blade Height	0.516 m	0.542	0.086	0.214	0.177	0.548	0.179	0.144	0.064	0.101	0.046	7.7
Mean Diameter	1.64 m	1.93	0.5	1.24	0.66	1.62	0.855	0.7	0.43	0.55	0.35	5.2
Boss Rates	0.6	0.6	0.78	0.77	0.66	0.59	0.725	0.72	0.8	0.75	0.835	0.5
Weak Points	Too large mean diameter Too long blade length Too large volume flow	Too low enthaply drop Too high pressure	Too low enthalpy drop Too high pressure	Mean diameter large	Pressure somewhat high	Too large mean diameter Too large volume flow Too long blade length		Pressure somewhat high	High pressure	Pressure somewhat high	Too high pressure	Too large mean diameter Too low pressure Too large volume flow
Probability of Realization	△	△	△	○	○	△	◎	○	△	○	△	X

◎ Realizable   ○ Probable   △ Hard   X Impossible

Table 9

Comparison of Working Fluids for Ideal 100-mm Cycle

Fluid	Cycle Efficiency (%)	High Pressure (psia)	Low Pressure (psia)	Pump Work (kw)	Mass Flow (lb/min)
Ammonia	3.72	118	81	1,079	317,600
Butane	3.82	29	20	859	976,000
Carbon Dioxide	2.89	779	609	36,003	2,873,000
Ethane	3.90	411	53	25,300	1,495,000
R-12	3.68	78	56	2,450	2,630,000
R-12/31	3.71	79	57	2,150	2,200,000
R-22	3.68	126	91	3,200	1,978,000
R-113	3.65	5	3	170	2,436,000
R-502	3.61	140	103	4,552	2,756,000
Propane	3.67	115	85	3,706	1,084,000
Sulphur Dioxide	3.72	45	30	634	1,041,000
Water	3.78	0.3	0.15	1.4	155,500

With respect to the environmental effects in the event of a massive working fluid spill, ammonia will have the smallest environmental impact as it is easily assimilated and dissipated in the ocean. The other three are known to be inferior to ammonia in this respect, but their precise environmental effects must be determined in advance if they are to be used as working fluids.

C. Turbines

Anderson[48] maintains that the turbine design problem has been essentially solved for the case of the closed cycle SSPP. Equivalent research on turbines to be used in conjunction with the Claude cycle SSPP has sorely lagged behind and only partially because it is a more difficult problem. Anderson[71] has presented an in-depth analysis of the concept, geometry, and optimization of the SSPP turbine, although no design plans have yet appeared for a full scale turbine. If ammonia is selected the major turbine problems become the turbine seals and turbine materials. In fact no matter what the working fluid selected, the SSPP cannot tolerate working fluid leakage by way of the turbine shaft seal.

The crucial material problem centers on the question as to whether or not turbine materials can be developed that will deteriorate no matter how wet the ammonia becomes.

The UMASS turbine, selected with the constraint that the working fluid is propane, will generate 30 megawatts per unit (Table 10). The cost is estimated at \$65/kw. However, if ammonia is chosen the cost decreases to \$35/kw (see Table 10).

There are many corporations that have many years of expertise in turbine design and development that are applicable to low ΔT, ΔP processes and there is little doubt that any one of them could produce an efficient turbine in a short time that would meet all the closed cycle SSPP requirements, if a contract with sufficient dollar incentives were awarded. On the other hand the Claude cycle turbine calls for some new concepts and materials and the situation is not as clear.

Table 10

Optimum Parameters for Turbines
with Ammonia and Propane as Working Fluids.[48]

A. Ammonia Axial Turbine - 100 megawatt total output
1. Specific Speed = 100. Specific Diameter = 1.0
2. Use three units of 33.3 megawatts each
3. Single storage, full periphery entry
4. Wheel diameter approximately 7 feet
5. Wheel rpm about 1800
6. Cost: \$35/kw
B. Propane Axial Turbine - 100 megawatt total output
1. Use three units of about 38 megawatts each
2. Single stage, full, periphery entry
3. Wheel diameter approximately 11.4 feet
4. Wheel rpm about 600
5. Cost: \$65/kw

D. Cold Water Supply and Pipe

It is best to begin this discussion by quoting Claude[7] who, it appears, was never uncertain about anything:

> "Further, the loss of head in the pipe and the excess of density of the column of cold water, for an output of 1 cubic meter and a speed of half a meter per second in the tube, caused a depression in the pit of but 3 meters, which shows how little energy is needed to bring up cold water, and how trivial are those objectors who condemn the process because of the tremendous amount of work they believe will be required to pump the cold water. I respectfully suggest that it is so long since these honorable gentlemen left school that they had better learn again the theory of communicating vessels. As a matter of fact, the above-mentioned results, obtained with a comparatively small tube in which the losses by friction are considerable, are very encouraging for the large pipes that will be used in the future."

Claude was correct; there do not appear to be any serious problems associated with the cold water supply.

The UMASS group has proposed a welded aluminum pipe aerodynamically shaped. The pipe for a 400 megawatt plant would be teardropped shaped and be 80 ft by 225 ft. Anderson has proposed, for a 100 megawatt plant, a 40 ft diameter pipe made of vertical 8 inch piping. The CMU group proposes a 60 ft diameter pipe for their 100 megawatt plant. The Japanese[25] have concluded that steel is unsuitable for the cold water pipe, because of the large diameter needed and they maintain that the installation cost is high in comparison to the cost of the pipe itself. They recommend the use of an FRP pipe they call Takata HF pipe.[72] This pipe can be shipped folded flat and then inflated and cured by air and heat at the SSPP construction site. They recommend that the upper portion of the pipe be reinforced near the top to protect the pipe against wave damage.

In any case one should design the pipe keeping in mind that certain potential problems may arise.[18]

(a) Vortex induced loading and the pipe's response

(b) Internal fluid flow and pipe instability

(c) The coupling of (a) and (b)

(d) Water hammer effects

(e) Response of pipe to wave induced motion of SSPP

(f) Fatigue and corrosion fatigue associated with the loading generated in (a) - (e) above.

For streamlined cross section pipe such as the UMASS design one should consider local subsurface currents (flow directions are not always constant with depth) that would tend to apply bending moments to the cold water pipe. Roels, et al.[32] report on successfully operating a small diameter 870 meter deep cold water pipe. The pipe is made of polyethylene and Roels[73] reports that it functions quite well.

It appears that the pipe problem can use some innovative thinking in terms of materials. To begin with a detailed analysis of the loads any given pipe will experience should be performed. One should consider flexible as well as relatively rigid materials. Lightweight composites might also do the job adequately. In fact, flexible material would possess the property of being immune to small bending and torsional stresses.

Insofar as the cold water pump is concerned there are no technical problems; only problems of optimizing the pump efficiency and lifetime. There are many companies which have experience in building the kind of pump required for SSPP application. Thus the pump, like the closed cycle turbine, appears to be a problem in the judicious selection of off-the-shelf hardware. On the other hand the design of the cold water pipe involves some innovative thinking, analysis and design, and the result could be greatly reduced cost and greatly increased reliability.

E. Mooring and Anchoring

The UMASS group has calculated the horizontal load on their SSPP at the Miami site. This load is on the order of 16,000,000 lbs. Some problems associated with mooring a system with these kinds of loads are discussed in Reference 18. The moorings needed by SSPPs must be easily deployable, have lifetimes of 25-40 years, be capable of being repaired relatively easily and have almost 100% reliability. The offshore oil platform technology has advanced to the point where one million pound mooring lines are state-of-the-art for semi-submersible platforms. One should take note of the fact that the Navy deployed a mooring in 6,000 ft of water and the mooring failed due to corrosion in 4.5 years.

The problems associated with anchoring and mooring can be solved, but the cost of the moor-anchor system that meets all requirements may be great. The moor and anchor (or massive weight resting on sea floor, as Heronemus' proposal for a football field size barge sunk to the bottom) system is one that will experience continuous dynamic (random) loading. The stress corrosion, corrosion fatigue and fatigue problems are critical especially near the sea floor where a significant static hydrostatic load will be superimposed upon the dynamic loads associated with the motion (vertical and horizontal) of the SSPP itself.

Further consideration should be given to floating SSPPs to ascertain if station keeping can be maintained with a minimum of power expenditure, or by directing the hot and cold water effluents. Placing SSPPs in currents such as the Gulf Stream should be carefully evaluated as to the loads imposed on mooring systems. Finally, the cost of mooring and anchoring may make the shore based SSPP the more attractive concept.

F Human Factors

Any ocean-based SSPP will have to be manned by a crew of about a dozen people. In the construction phase many more people will be needed. The SSPP must be designed so that rescue and escape, in the event of an emergency, can be accomplished quickly and efficiently. One must take preventive measure against the leakage of hazardous working fluids. Some consideration should be given to underwater escape and submarine rescue.

The SSPP should be designed so that the maximum possible number of repairs can be made without the use of divers. The SSPP can also be designed to be capable of rising to the surface by say, uncoiling part of the mooring cable, so as to make repairs on the surface. The SSPP could also use this system to go deeper to escape from especially severe (50 year) storms.

It is expensive to equip an ocean-based plant for human habitation and even more expensive to pay a crew to live on the SSPP. One will have to design the SSPP so as to minimize the crew size. An optimization study will have to be made (three eight-hour shifts?) to get the required tasks performed with a minimum of personnel and still have sufficient manpower available to deal with emergency situations.

IX. COMPLEMENTARY AND AUGMENTED SSPP ENERGY SYSTEM

The primary objective and motivation for building and operating an SSPP is to provide the U.S. with an additional source of energy to satisfy demand and help make the U.S. self-sufficient in energy. To accomplish this end it is incumbent upon one to consider combining certain energy sources and systems to obtain as large and concentrated an energy source as possible. A schematic summary of the various concepts of systems that can augment or increase the efficiency of the SSPP plus concepts involving systems to be constructed with or in conjunction with an SSPP, that can produce power at a lower cost than if built alone, is shown in Figure 23. Another systems schematic from Reference 74 illustrates some associated concepts in Figure 24. Figures 25 and 26 illustrate a Japanese systems concept for an atoll (in Micronesia) based SSPP supporting mariculture and industrial operations.

It has been proposed to build nuclear power plants in the ocean, just offshore and on land, but ocean cooled. There are many ocean cooled nuclear power plants. A number of offshore nuclear power plants have been designed and are scheduled to be built in the near future. These plants use the tepid ocean water for cooling purposes. Fossil fuel plants abound on our coasts that also use the tepid sea water for cooling purposes. It seems obvious that this water (warmer than the tepid ocean water) could be used to increase the ΔT one has to work with (see Figure 27). In effect, the SSPP could act as a partial bottoming cycle for fossil or nuclear power plants. Depending on the size of the power plant the ΔT increase might not be very big, but every little bit will help increase the efficiency of the SSPP. It seems to make good sense to make use of these power plant's thermal effluent.

Many prime SSPP sites are over or near geothermal areas, such as Hawaii. At these sites one can construct a geothermal power plant in conjunction with an SSPP. The effluent from this plant may be used to increase the ΔT the SSPP must work with. In the event a geothermal power plant is not built the geothermal water can be used directly to increase the operating ΔT of the SSPP.

The use of solar ponds, as suggested by Barnea,[46] is not practical. Temperatures up to 95°C can be obtained at the bottom of a solar pond. However, the quantity of water at this temperature is small and hence its potential influence on the SSPP's operating ΔT would be insignificant.

Wind power plants can be built in conjunction with either the land-based or the ocean-based SSPP (see Figure 24). Other energy producing systems can also be joined to the SSPP as shown in Figure 23. In the ocean, as long as one has an SSPP on the site, one might as well erect some windmills there.

There is a research program underway to design and develop plans for a floating city off the coast of Hawaii (see Figure 28). It is planned to use oil burning power generation equipment for this floating city. It seems superfluous to build an oil burning plant over a prime SSPP site. In fact one could combine the floating city concept with some of the ideas indicated in Figures 23 and 25 to design an industrial and residential area equivalent to the size of a small city.

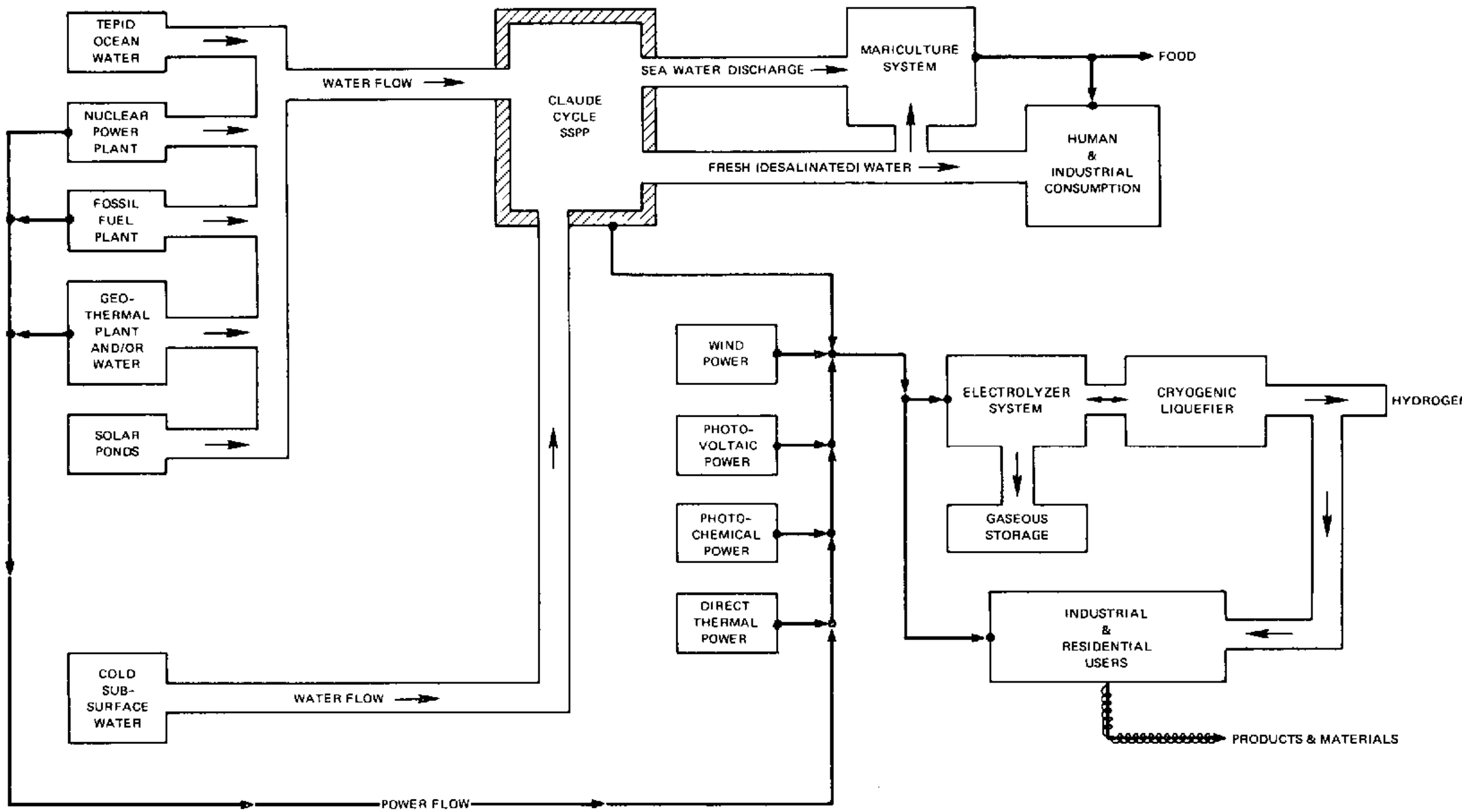

Figure 23. SSPP Complemented and Augmented Energy System Schematic

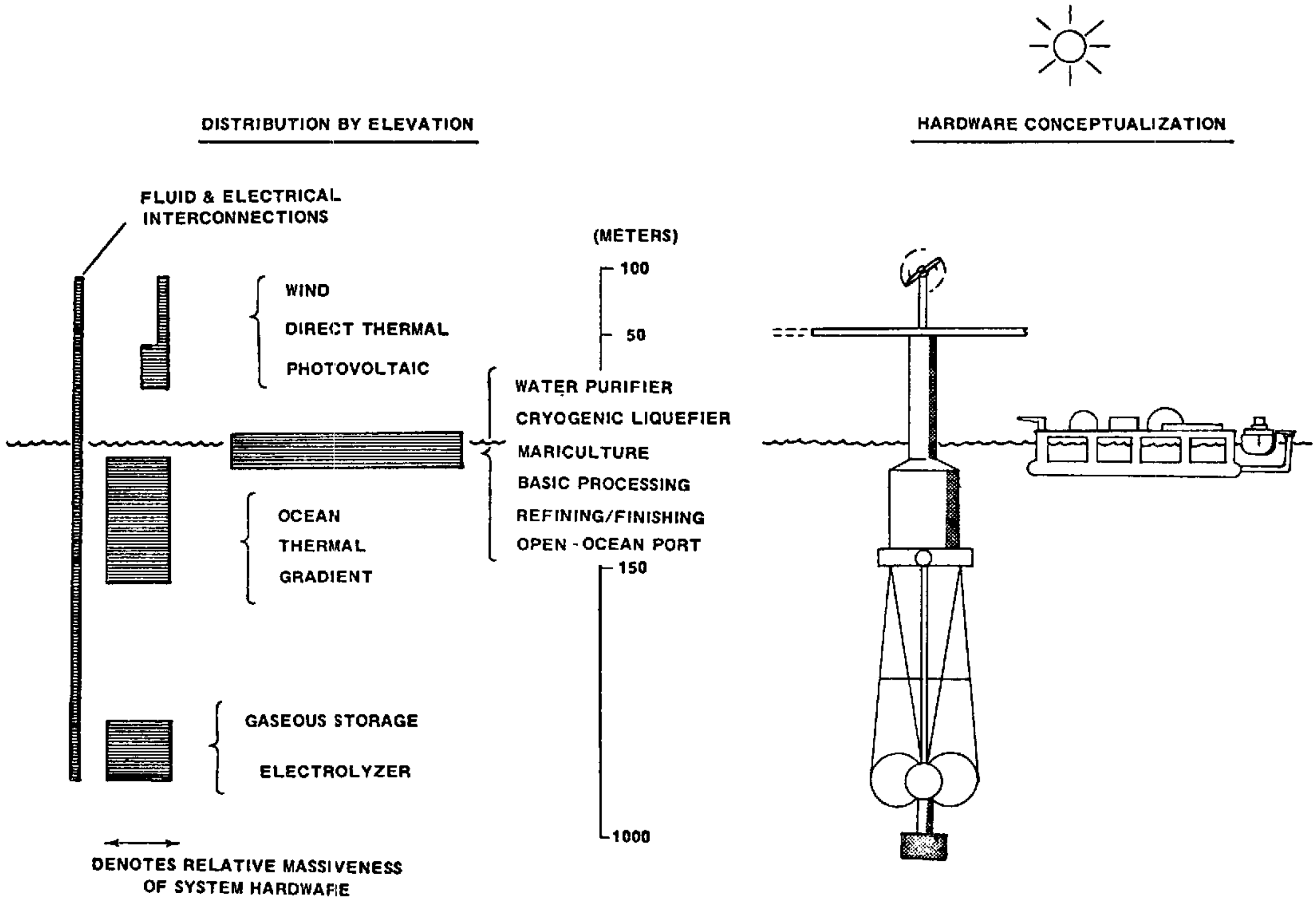

Figure 24. Typical Systems Location

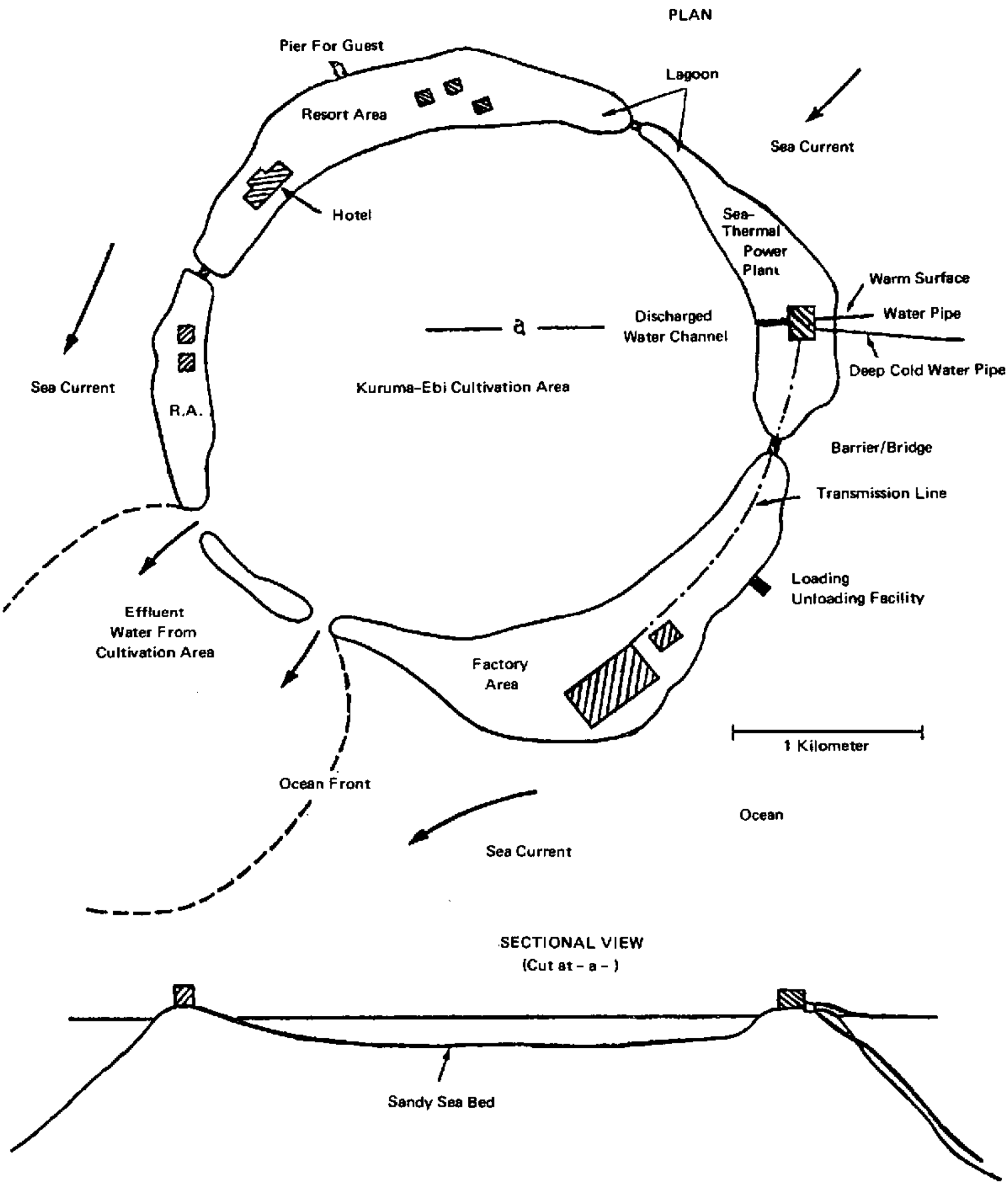

Figure 25. A Model Marine Industrial Complex

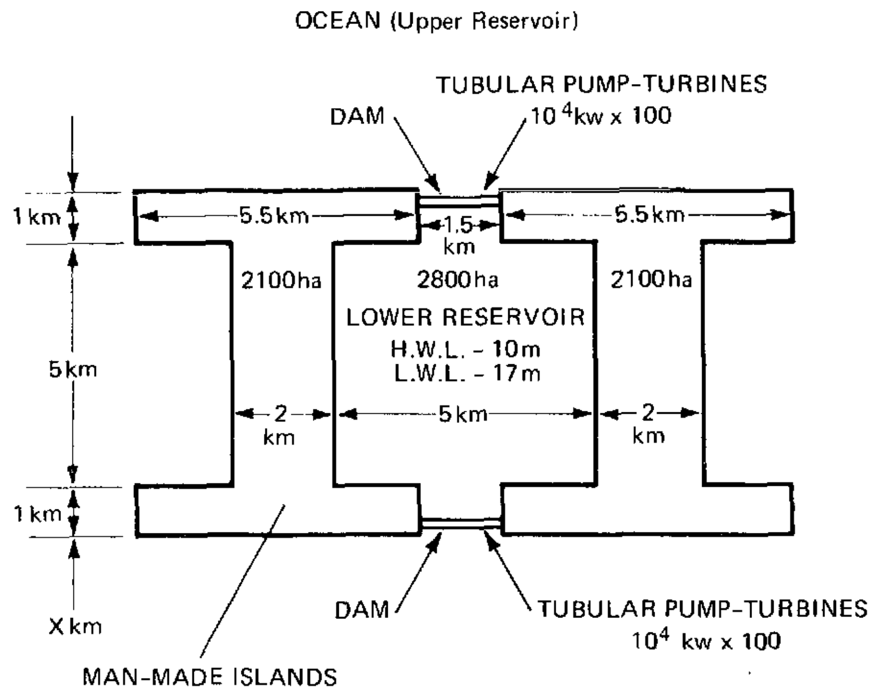

Figure 26. A Plan of Ocean Pumped Storage Plant

One should also look at the industrial thermal effluents associated with the chemical, metal and other industries that can be operated at SSPP sites and serve to increase the SSPP's operating ΔT.

X. CONCLUSIONS AND RECOMMENDATIONS

A. The Energy Shortage

Although a worldwide energy shortage will develop in the next few decades, it does not appear that the U.S. will face any significant shortages until after the year 2020. If the breeder reactor and solar energy programs prove successful, the U.S. will achieve self-sufficiency prior to the year 2000 and maintain self-sufficiency for an extended period of time.

The main reason for going ahead with concepts like the SSPP is that the world demand for energy, especially in developing nations, is accelerating. The more self-sufficient the U.S. is in energy the more energy that will be made available to raise the standards of living in other nations. This is an important reason for going ahead with solar energy schemes. Also, since many of the developing nations border on prime SSPP sites in the tropics, the SSPP is an inexpensive method of obtaining the necessary energy.

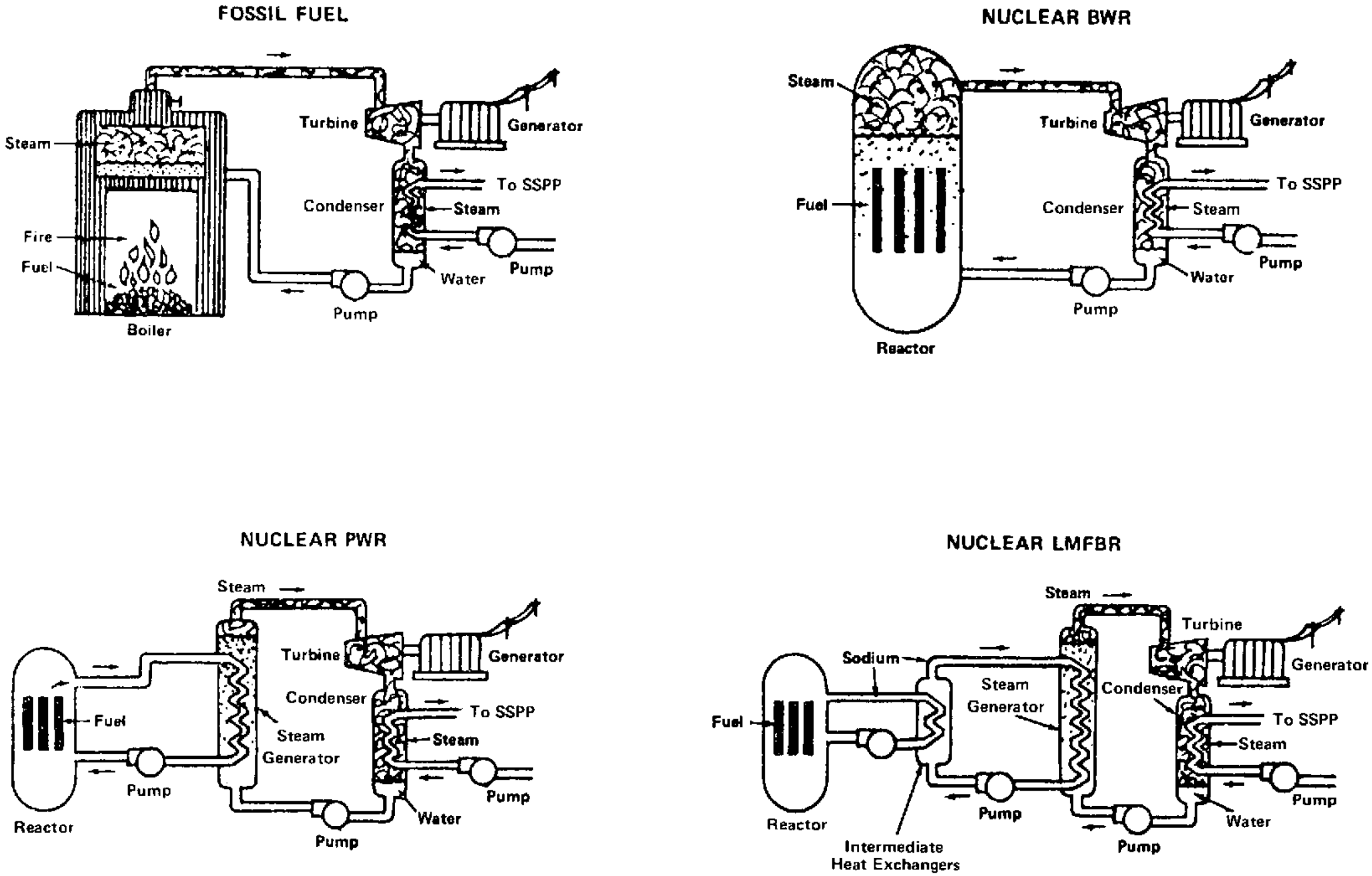

Figure 27. Types of Steam-Electric Generating Plants

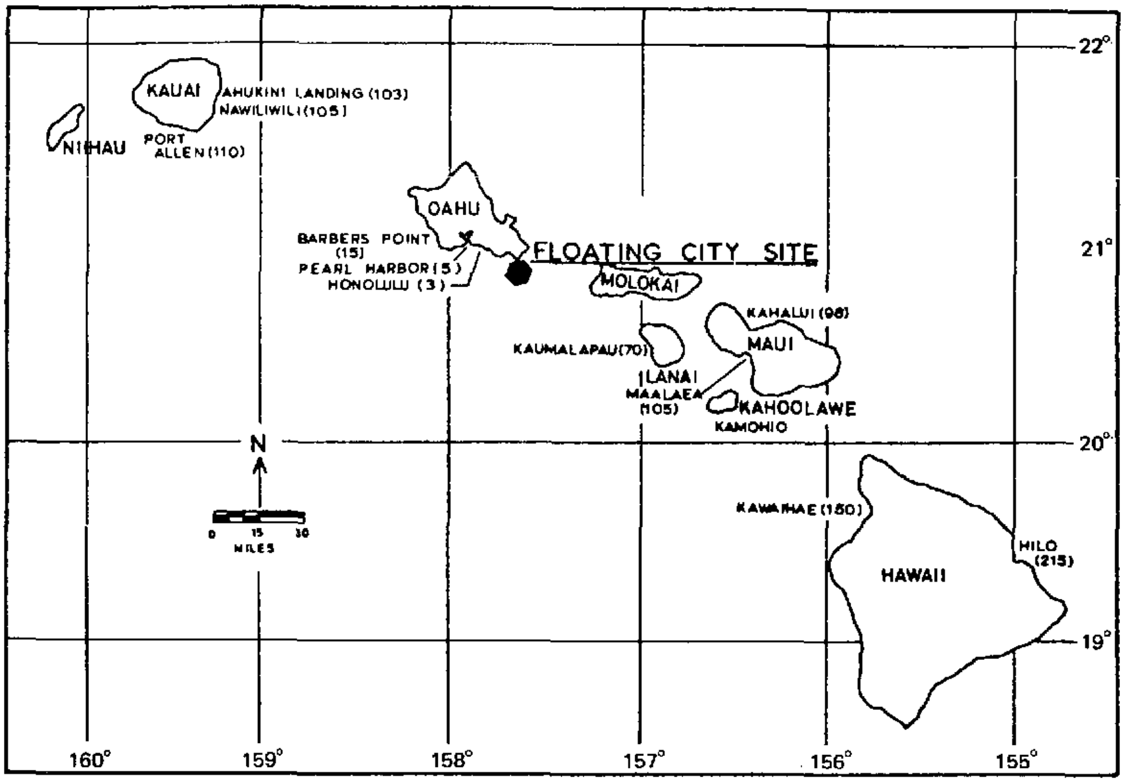

Figure 28. Map of the Hawaiian Islands with Locations of Possible Floating City Sites and the Prime Site Selected in Reference 75

B. The Pollution Problem

It must be proven that artificial upwelling on a massive scale will not cause any ecological disasters and that there are no detrimental effects due to the operation of the SSPP. Then one may claim that the SSPP is non-polluting and clearly superior to fossil and nuclear power plants in this respect.

C. Cost

The SSPP is very economical (inexpensive) when compared to the costs of other solar energy plants (except perhaps wind power) and fossil and nuclear fuel plants. However, it is difficult to back up this claim without a good size SSPP in operation.

D. Mariculture

It is recommended that any SSPP built have a mariculture system designed in conjunction with the power plant itself. As the world food shortage intensifies it becomes clear that the value of the food grown with the aid of the artificially upwelled water will exceed the value of power generated, both in human and dollar terms. It would be a gross neglect of responsibility not to proceed with mariculture research and development in conjunction with research and development on the SSPP and its components.

E. Siting

As stated in Section IV the sites recommended for the location of the first demonstration SSPPs are:

- The south coast of Puerto Rico
- The north coast of St. Croix, U.S. Virgin Islands
- Hawaiian Islands (various sites)
- U.S. Pacific Islands
  - (1) Yap Island
  - (2) Guam
  - (3) Western Samoa (Upolu)
  - (4) Various other Pacific Islands and atolls are also viable sites.
- Miami, Florida

The Miami site is low on the priority list because of the smaller ΔT encountered there. Once the SSPP concepts have been sufficiently proved and the state-of-art advanced so as to provide SSPPs with increased efficiencies, the Miami site will become attractive because of its proximity to a great population center and the U.S. mainland. There is a sufficient drain on U.S. energy supplies on Puerto Rico to justify it as the prime site. All fossil fuels saved because of the SSPP's operation can be used on the U.S. mainland. The same reasoning holds for the Hawaiian Islands. As for the U.S. Pacific Islands, the proximity of Japan gives a market for large amounts of SSPP energy. With careful planning this underdeveloped area could become the "Kuwait of the Pacific."

F. Law

The legal problems that must be resolved are:

- Ownership of SSPP and surrounding areas outside territorial waters as they are presently defined.
- A system whereby one could retain rights to (ownership) the fruits of the mariculture operation and prevent arbitrary fishing vessels from reaping

the benefits of the SSPP's upwelled water. This must be done if private industry is to be encouraged to take a leadership role in SSPP design, construction and operation.

G. Materials

It is recommended that concrete be the basic material used in the structure of the SSPP. Concrete — the specific characteristics and type can be decided on when the power plant specifications are finalized — is the one material that has proved it can perform its function underwater for long periods of time without maintenance. The cost is also low compared to some materials suggested.

Materials for the turbine need to generate power for the open (Claude) cycle SSPP have yet to be thoroughly researched. This is an important area where lifetimes, efficiencies and weight are considerations, and where results can be obtained quickly.

It is critical to find an appropriate material to use in the mooring system for an ocean-based SSPP. There has not yet been put forth a material appropriate for this purpose that will perform its function for 20 years or more.

Other material problems will be discussed under the component headings.

H. The Nitinol SSPP

The Nitinol engine powered SSPP is an interesting concept that may be successful. The major drawback here is the low ΔT one has to work with and the performance of the material in that narrow temperature range. Any successful Nitinol engine would have many applications in addition to power generation. Therefore, research should be encouraged in this area. The attractiveness of the Nitinol concept is on a par with that of closed cycle power production plant. It has many of the same drawbacks as the closed cycle, but does not need the complex heat exchangers essential for closed cycle SSPP operation. The Nitinol SSPP should be looked into closely.

I. The Claude Cycle SSPP

The Claude Cycle SSPP should be given top priority in research, development and construction. It possesses many advantages over any other competing SSPP system. A few major advantages are (see Figures 7 and 29):

- Heat exchangers are not needed.
- There is no ΔT loss due to heat exchanger operation.

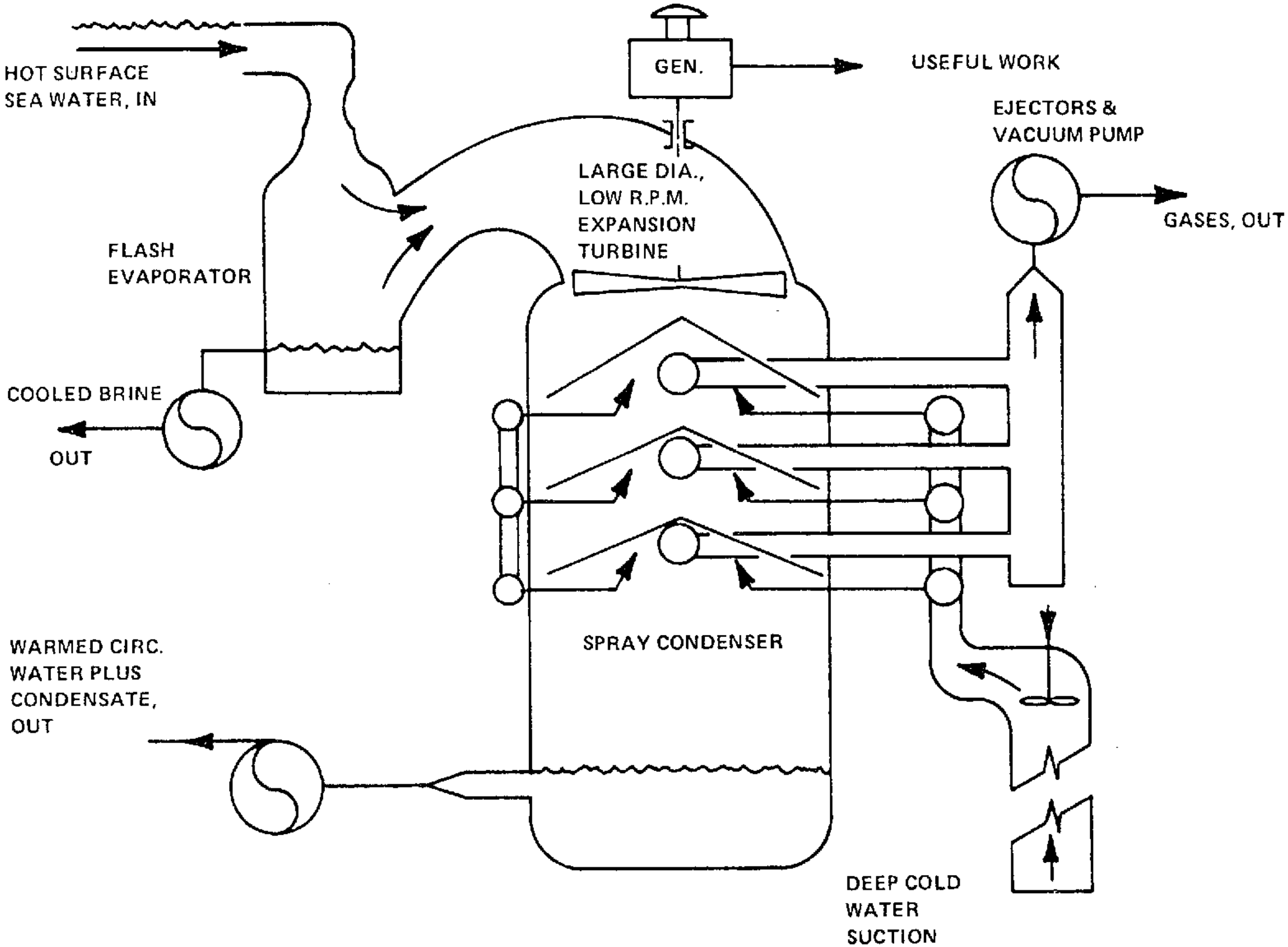

Figure 29. The Claude Ocean Thermal Difference Process

- Fresh (desalinated) water is produced as a byproduct.
- It is relatively insensitive to biofouling.
- Its loss of function due to corrosion is relatively low.
- It is the only SSPP design that was actually proven viable in operation.

The objections to this process center around the large size turbines needed. However, the advantages of the Claude cycle power plant greatly outweigh its disadvantages. Claude cycle research and development should take priority over closed-cycle and Nitinol SSPP research and development.

J. The Closed Cycle SSPP

The main problem associated with any closed cycle SSPP design is the design of the heat exchangers. The basic problems are:

- One loses half of the ΔT in the heat exchanger operation. A 20°C ΔT is degenerated into a 10°C ΔT.
- There has not yet appeared a demonstrated and economic means of preventing the heat exchangers from suffering the occurrence of biofouling. Even the smallest amount of biofouling destroys the heat transfer ability of the heat exchangers.
- The corrosion of the heat exchangers is a serious problem in maintaining heat exchanger efficiency.
- The closed cycle SSPP does not produce fresh water as a byproduct.
- One must contend with potentially dangerous working fluid leaks.
- In an efficient heat exchanger, clogging of the tubes is a problem and manufacturing costs may be high.
- One does not seem to gain much by even the most exotic methods, in adopting heat transfer augmentation techniques. Innovative ideas such as those applying heat pipes and thermosyphons do not yield any great increase in efficiency.

Thus with the present state-of-the-art and the problems confronting the heat exchanger designer, it does not appear that a closed cycle SSPP can be designed that could operate for any significant length of time without having to undergo massive maintenance and repair (takedown) operations periodically.

Research and development should continue on the closed cycle SSPP operation, but it should be on a parity with that of the Nitinol concept. First priority still should be given to the Claude (open) cycle SSPP.

K. Working Fluids

Ammonia is the most efficient working fluid proposed for SSPP operation. This combined with the fact that it is the least harmful working fluid, with respect to the environment, in event of a working fluid spill would seem to tip the scales in favor of ammonia. Nonetheless it has its drawbacks in that it is very corrosive when wetted and is hazardous to humans in the event of leakage. But the SSPP efficiency is so low as to make the use of ammonia almost mandatory in a closed cycle SSPP demonstration plant.

L. Turbines

There does not appear to be any difficulty with closed cycle turbines. A great deal of work remains to be done on open cycle turbines, however.

M. Cold Water

One must come up with better and lighter materials for the cold water pipe. As the only function of the cold water pipe is to separate the upwelling cold water from the surrounding warmer waters, it does not appear that anything of great structural strength is needed. A new direction must be taken in cold water pipe design so as not to get locked into massive metal or concrete pipes.

This cold water, as described above, will be used for mariculture purposes; either in land ponds or in the sea itself.

N. Mooring and Anchoring

The mooring and anchoring problem is critical for an ocean based SSPP. Various methods of mooring and anchoring have been proposed and no attempt will be made here to distinguish between them. All the proposed systems seem to have one common drawback: the moorings are metallic and are dynamically loaded in tension in an extremely corrosive environment. These facts combine to give any mooring system a low probability of survival (high probability of fracture) over time periods of the order of 5 years. If the SSPP is to have a lifetime of from 20 to 50 years some advances in mooring systems and materials must be made. More experience should be obtained on mooring very large systems like the SSPP; systems that exert large loads on the mooring and anchoring materials. It would not be beneficial to advocates of the SSPP to have a demonstration SSPP break loose of its mooring and float away to destruction. A mooring failure should be considered a single point failure and if one is to design an SSPP with single point failure components built into it, then those critical components should be extremely reliable. Failure mode analyses must be performed and carefully documented on these components like the mooring-anchoring system. This brings us to the next recommendation.

O. Land or Sea

Is it better to build a land-based SSPP or an ocean-based SSPP? The level of the state-of-the-art in 1974 induces me to recommend that land-based SSPPs be given first priority with respect to construction. Research should continue on ocean-based systems and an effort should be made to prove the long term viability of ocean-based SSPPs. The advantages of a land-based SSPP are:

- No mooring and anchoring problems.
- Lower construction costs and faster construction time.
- Cold water pipe design problems are simplified.
- Controlled mariculture in pools on land is possible.
- Power delivery simplified.
- Fresh water transport to demand areas simplified.
- Human factors problems simplified (no need for rescue systems or special training).
- Maintenance problems simplified (no underwater repairs).
- Better publicity (tours, press conferences, etc.) to sell the SSPP to the public.

P. Human Factors

A land-based SSPP (especially of the open cycle type) will have human factors problems equivalent to those in a standard power plant. The ocean-based SSPP would have more difficult human factors problems. These problems are, however, encountered on off-shore oil platforms and the oil industry seems to have solved their problems nicely. Our conclusion is, therefore, that there are no major human factors problems associated with SSPP operation.

Q. Complementary and Augmented SSPP Energy Systems

It is recommended that to make an impact on the nation's energy production habits an attempt be made to squeeze out every kilowatt possible from any means at our disposal as described in Section IX.

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