DSE-2421-T1(App.)

OCEAN THERMAL ENERGY CONVERSION MISSION ANALYSIS STUDY. PHASE II

Appendices

MASTER

March 1978

Work Performed Under Contract No. EX-76-C-01-2421

General Electric Company—Tempo
Center for Advanced Studies
Washington, D. C.

U.S. Department of Energy

Solar Energy

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MISSION ANALYSIS STUDY;
PHASE II.

APPENDICES

MARCH 1978

PREPARED FOR:

U.S. DEPARTMENT OF ENERGY
DIVISION OF SOLAR ENERGY

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PREPARED BY:

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APPENDICES

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APPENDIX A

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OTEC-MISSION ANALYSIS ENERGY CARRIER COST AND MARKET PENETRATION ANALYSIS

Final Report

by

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Under Subcontract to

General Electric Company/TEMPO
816 State Street
Santa Barbara, California 93109

General Electric/TEMPO Subcontract No. 29412

April 1979

Prepared for the
UNITED STATES DEPARTMENT OF ENERGY
Under Contract No. EX-76-C-01-2421

EXECUTIVE SUMMARY

This is the final report under the General Electric Company-TEMPO (GE-TEMPO) Subcontract No. 29412. The purpose of this subcontract was to examine the economics of using hydrogen, ammonia, and molten salts as carriers for ocean thermal energy conversion (OTEC) produced energy. These carriers were to be considered under a set of assumptions that specified the locations of the OTEC sites and energy destinations, and the performance and size of the OTEC platforms. The economics of the OTEC platforms and energy carriers were assumed to be based upon advanced long range improved technology (ALRIT), 10 to 40 mills/kWhr electrical power on the OTEC platform, a nominal 100-MW capacity rating for each OTEC platform, and single rather than clustered platforms. The emphasis was to determine whether these carriers could be economically viable with small, start-up OTEC platforms in the period 1985 to 2000.

The effort for this subcontract was performed in conjunction with GE-TEMPO Subcontract 29343, which examined the economics of using a lithium/lithium hydroxide carrier. The results of that subcontract are shown in Appendix A-1. The purpose of both subcontracts was to provide the Department of Energy (DOE), through GE-TEMPO, with our estimates of the ability of introductory stage OTEC sites using these carriers to provide competitive energy to the United States. The energy delivered by these carriers could be in the form of electricity, heat, fuel, or an energy-intensive commodity.

The economics were examined for a number of potential OTEC platform locations and potential energy destinations. The shipping distances ranged from 10 to close to 5000 statute miles; hence, the transportation distances made a substantial impact on the costs of the delivered carriers. The choice of 100-MW OTEC platforms operating as single units made a large impact on the ultimate carrier costs. By clustering OTEC plants with over 1500-MW nominal capacity in groups, tanker ships can often be used in place of ocean-going barges. Further, by using OTEC plants with unit capacities in excess of 100-MW, economics-of-scale can be realized on the costs of the basic OTEC plant and the carrier production plants. The decision to limit the study to single 100-MW plants was based upon the belief that the larger, clustered, or grazing plants would not reach commercial maturity within the 1980-2000 time frame of this study.

Tables ES-1 through ES-7 present the results of our calculations of the costs of the delivered carriers either as electricity or as a fuel or commodity. (Note that the lithium/lithium hydroxide carrier produces electricity only.)

Table ES-1. OTEC PRODUCED LIQUID HYDROGEN DELIVERED TO VARIOUS SITES ($\$/10^6$ Btu, 1976 Dollars)

OTEC Site	Net Capacity Factor	Annual Electricity Production, 10^6 kWhr	Annual Liquid Hydrogen Production, 10^3 Tons	Annual Liquid Hydrogen Delivery, 10^3 Tons	Destination	Distance, Statute Miles	Delivered Cost of Liquid Hydrogen, Conservative Assumptions ($\$/10^6$ Btu): 10 Mills	20 Mills	30 Mills	40 Mills	Delivered Cost of Liquid Hydrogen, Optimistic Assumptions ($\$/10^6$ Btu): 10 Mills	20 Mills	30 Mills	40 Mills
Key West	0.750	657	12.31	11.92	New York	1377	21.32	25.83	30.34	34.85	18.90	23.42	27.93	32.44
			15.60*	15.60	Miami	250	10.74	14.42	17.87	21.32	10.74	14.42	17.87	21.32
			12.31	11.92	New Orleans	603	17.89	22.40	26.91	31.42	15.94	20.45	24.96	29.47
			12.31	11.92	Houston	803	21.16	25.67	30.18	34.35	18.68	23.15	27.66	32.17
West Florida	0.720	631	11.82	11.44	Miami	516	17.71	22.22	26.74	31.25	16.06	20.59	25.10	29.62
			14.97*	14.97	New Orleans	345	13.40	16.85	20.05	23.75	13.40	16.85	20.05	23.75
			11.82	11.82	Houston	610	18.52	23.11	27.55	32.06	16.4[illegible]	21.00	25.45	29.96
Miami	0.792	694	13.00	12.59	New York	1145	20.47	24.98	29.49	34.00	18.04	22.55	27.06	31.57
			16.47*	16.47	Miami	10	5.39	8.89	12.29	15.51	5.39	8.89	12.29	15.51
			13.00	12.59	New Orleans	852	20.29	24.80	29.31	33.82	17.86	22.37	26.88	31.39
			13.00	12.59	Houston	1052	20.42	24.93	29.44	33.95	17.98	22.49	27.00	31.52
New Orleans	0.630	552	10.34	10.01	Miami	852	24.36	28.87	33.39	37.90	21.30	25.81	24.79	34.84
			13.10*	13.10	New Orleans	58	6.67	10.12	18.57	17.02	6.67	10.12	18.57	17.02
			10.34	10.01	Houston	403	18.46	22.97	27.48	30.99	16.72	21.23	25.74	30.26
Brownsville	0.635	557	13.21*	13.21	Houston	357	14.72	18.16	21.61	24.93	14.72	18.16	21.61	24.93
Puerto Rico	0.785	688	12.89	12.47	New York	1609	20.63	25.15	29.66	34.19	18.18	22.70	27.21	30.73
			12.89	12.47	Miami	1104	20.53	25.04	29.56	34.07	18.06	22.57	27.10	31.60
			12.89	12.47	New Orleans	1772	20.70	25.21	29.73	34.37	18.24	22.75	27.26	31.78
			12.89	12.21	Houston	1972	21.23	25.30	30.45	34.33	18.72	22.84	27.94	31.87
Hawaii	0.812	711	13.33	12.31	Los Angeles	2953	25.95	30.68	35.40	40.13	22.21	26.93	31.66	36.38
Brazil	0.791	695	13.02	11.49	New York	4253	34.61	39.56	44.51	49.46	28.58	33.53	38.48	43.43
			13.02	11.67	Miami	3974	31.46	36.34	41.21	46.08	26.20	31.10	35.95	40.82
			13.02	11.31	New Orleans	4829	37.22	42.25	47.27	52.30	30.43	35.46	40.49	45.52
			13.02	11.31	Houston	4966	37.31	42.33	48.95	52.39	30.52	35.54	40.57	45.60

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* Gaseous hydrogen.

All "tons" in this report are "short tons."

Table ES-2. OTEC PRODUCED LIQUID AMMONIA DELIVERED TO VARIOUS SITES ($/ton, 1976 Dollars)

OTEC Site	Net Capacity Factor	Annual Electricity Production, 10^6 kWhr$_e$	Annual Liquid Ammonia Production, 10^3 tons	Annual Liquid Ammonia Delivery, 10^3 tons	Destination	Distance, statute miles	Delivered Costs of Liquid Ammonia: 10 Mills ($/ton)	20 Mills ($/ton)	30 Mills ($/ton)	40 Mills ($/ton)
Key West	0.750	657	77.20	77.20	New York	1377	199	284	369	454
					Miami	250	179	264	349	435
					New Orleans	603	185	270	355	440
					Houston	803	188	273	358	443
West Florida	0.720	631	74.11	74.11	Miami	516	186	272	357	442
					New Orleans	345	184	269	354	439
					Houston	610	189	274	359	444
Miami	0.792	694	81.52	81.52	New York	1145	188	273	359	444
					Miami	10	173	258	344	429
					New Orleans	852	182	267	352	437
					Houston	1052	186	271	356	442
New Orleans	0.640	552	64.85	64.85	Miami	852	207	292	377	462
					New Orleans	58	196	282	367	452
					Houston	403	199	283	368	453
Brownsville					Houston	357	197	282	367	452
Puerto Rico	0.785	688	80.80	80.80	New York	1609	196	281	367	452
					Miami	1104	188	273	358	444
					New Orleans	1772	197	282	367	452
					Houston	1972	197	282	374	453
Hawaii	0.812	711	83.58	83.58	Los Angeles	2953	198	283	363	453
Brazil	0.793	695	81.63	81.63	New York	4253	228	313	398	483
					Miami	3974	227	312	397	482
					New Orleans	4829	238	323	409	494
					Houston	4966	239	324	409	494

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Table ES-3. OTEC PRODUCED PROCESS HEAT VIA MOLTEN SALTS BRIDGE DELIVERED TO VARIOUS SITES ($\$/10^6$ Btu, 1976 Dollars)

OTEC Site	Net Capacity Factor	Annual Electricity Production, 10^6 kWhr$_e$	Annual Molten Salts Production, 10^6 kWhr$_t$	Annual Molten Salts Delivery, 10^6 kWhr$_t$	Destination	Distance, Statute Miles	Delivered Cost of Molten Salts: 10 Mills	20 Mills	30 Mills	40 Mills
							$\$/10^6$ Btu			
Key West	0.750	657	519.95	519.95	New York	1377	45.80	49.51	53.21	56.91
					Miami	250	14.62	18.32	22.02	25.73
					New Orleans	603	25.65	29.35	33.05	36.76
					Houston	803	30.01	33.71	37.42	41.12
West Florida	0.720	631	499.15	499.15	Miami	516	23.07	26.79	30.48	34.18
					New Orleans	345	19.40	23.10	26.80	30.51
					Houston	610	26.83	30.53	34.23	37.94
Miami	0.792	694	549.07	549.07	New York	1145	39.38	43.10	46.78	50.48
					Miami	10	4.66	8.37	12.06	16.03
					New Orleans	852	30.13	33.84	37.54	41.24
					Houston	1052	36.28	39.98	46.68	47.38
New Orleans	0.630	552	436.76	436.76	Miami	852	36.93	40.63	44.33	48.04
					New Orleans	58	8.22	11.93	15.63	19.33
					Houston	403	24.66	28.36	32.06	35.77
Brownsville	0.635	557	440.22	440.22	Houston	357	22.12	25.83	29.53	33.23
Puerto Rico	0.785	688	544.21	544.21	New York	1609	48.47	52.17	55.88	59.58
					Miami	1104	38.26	41.96	45.66	49.36
					New Orleans	1772	51.24	54.94	58.65	62.35
					Houston	1972	56.61	60.31	64.01	67.72
Hawaii	0.812	711	562.93	562.93	Los Angeles	2953	75.19	78.89	82.59	26.29
Brazil	0.793	695	549.76	549.76	New York	4253	104.00	107.60	111.31	115.00
					Miami	3974	98.00	101.20	104.91	108.62
					New Orleans	4829	117.00	120.46	124.16	127.87
					Houston	4966	119.00	122.80	126.52	130.22

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Table ES-4. OTEC ELECTRIC POWER* DELIVERED TO DESTINATION BUSBAR VIA LIQUID HYDROGEN BRIDGE (Cost/kWhr, 1976 Dollars)

OTEC Site	Net Capacity Factor	Annual Electricity Production, 10^6 kWhr	Annual Liquid Hydrogen Production, 10^3 tons	Annual Electricity Delivery, 10^6 kWhr	Destination	Distance, Statute Miles	Delivered Electricity Cost, Conservative Assumptions: 10 Mills (mills/kWhr)	20 Mills	30 Mills	40 Mills	Delivered Electricity Cost, Optimistic Assumptions: 10 Mills (mills/kWhr)	20 Mills	30 Mills	40 Mills
Key West	0.750	657	12.31	189.94	New York	1377	175	210	244	279	157	191	256	260
			15.60†	223.48	Miami†	250	101	131	160	190	101	131	160	190
			12.31	189.94	New Orleans	603	149	183	218	253	134	168	203	238
			12.31	189.94	Houston	803	174	208	243	275	155	189	224	258
West Florida	0.720	631	11.82	182.35	Miami	516	148	182	217	252	135	170	205	239
			14.97†	214.54	New Orleans†	345	122	152	181	211	122	152	181	211
			11.82	182.35	Houston	610	154	189	223	258	138	173	207	242
Miami	0.792	694	13.00	200.58	New York	1145	168	203	237	272	149	184	219	253
			16.47†	235.99	Miami†	10	53	83	112	142	53	83	112	142
			13.00	200.58	New Orleans	852	167	201	236	270	148	183	217	252
			13.00	206.58	Houston	1052	168	202	237	271	149	184	218	253
New Orleans	0.630	552	10.34	159.55	Miami	852	201	235	270	304	177	212	246	281
			13.10†	187.72	New Orleans†	58	66	96	125	154	66	96	125	154
			10.34	159.55	Houston	403	150	190	225	259	142	177	211	246
Brownsville	0.635	556	13.21†	189.21	Houston†	357	135	164	194	223	135	164	194	223
Puerto Rico	0.785	688	12.89	198.81	New York	1609	169	204	239	273	150	185	220	254
			12.89	198.81	Miami	1104	168	202	238	272	150	184	219	263
			12.89	198.81	New Orleans	1772	170	204	239	274	151	185	220	255
			12.89	194.66	Houston	1972	174	209	245	280	155	190	225	261
Hawaii	0.812	711	13.33	196.21	Los Angeles	2953	210	246	283	319	181	218	254	290
Brazil	0.793	695	13.02	183.14	New York	4253	277	315	353	391	231	269	307	345
			13.02	186.01	Miami	3974	253	290	328	365	213	250	287	325
			13.02	180.27	New Orleans	4829	298	336	375	413	246	284	323	361
			13.02	180.27	Houston	4966	298	337	375	414	246	285	323	362

* 100 MW plant using busbar costs of 10, 20, 30, and 40 mills/kWhr. Electricity costs are for baseload.

† Gaseous hydrogen.

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Table ES-5. OTEC ELECTRIC POWER* DELIVERED TO DESTINATION BUSBAR VIA LIQUID AMMONIA BRIDGE (Cost/kWhr, 1976 Dollars)

OTEC Site	Net Capacity Factor	Annual Electricity Production, 10^6 kWhr	Annual Liquid Ammonia Production, 10^3 tons	Annual Electricity Delivery, 10^6 kWhr	Destination	Distance, Statute Miles	Delivered Electricity Cost, Conservative Assumptions† (mills/kWhr): 10 Mills	20 Mills	30 Mills	40 Mills
Key West	0.750	657	77.20	147.76	New York	1377	127	172	216	261
					Miami	250	117	162	206	251
					New Orleans	603	120	164	209	253
					Houston	803	121	166	210	255
West Florida	0.720	631	74.11	141.85	Miami	516	122	166	211	255
					New Orleans	345	120	165	209	254
					Houston	610	123	168	212	257
Miami	0.792	694	81.52	156.03	New York	1145	121	165	210	254
					Miami	10	113	157	202	246
					New Orleans	852	117	162	206	251
					Houston	1052	120	164	208	253
New Orleans	0.630	552	64.85	124.12	Miami	852	136	180	225	269
					New Orleans	58	131	175	220	264
					Houston	403	131	176	220	265
Brownsville	0.635	557	65.36	125.10	Houston	357	131	175	220	264
Puerto Rico	0.785	688	80.80	154.66	New York	1609	125	169	214	258
					Miami	1104	121	165	210	254
					New Orleans	1772	125	170	214	259
					Houston	1972	128	170	214	259
Hawaii	0.812	711	83.58	159.97	Los Angeles	2953	125	169	214	258
Brazil	0.793	695	81.63	156.23	New York	4253	141	186	230	275
					Miami	3974	141	185	230	274
					New Orleans	4829	147	191	236	280
					Houston	4966	147	191	236	280

* 100-MW plant using busbar costs of 10, 20, 30, and 40 mills/kWhr. Electricity costs are for baseload.

† Optimistic assumptions were not made for molten salts.

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Table ES-6. OTEC ELECTRIC POWER* DELIVERED TO DESTINATION BUSBAR VIA MOLTEN SALTS BRIDGE
(Cost/kWhr, 1976 Dollars)

OTEC Site	Net Capacity Factor	Annual Electricity Production, 10^6 $kWhr_e$	Annual Molten Salts Production, 10^6 $kWhr_t$	Annual Electricity Delivery, 10^6 kWhr	Destination	Distance, Statute Miles	Delivered Electricity Cost, Conservative Assumptions† 10 Mills	20 Mills	30 Mills	40 Mills
							mills/kWhr			
Key West	0.750	657	519.95	181.98	New York	1377	456	492	528	564
					Miami	250	152	188	224	260
					New Orleans	603	260	296	332	368
					Houston	803	302	338	374	410
West Florida	0.720	631	499.15	174.70	Miami	516	235	271	307	343
					New Orleans	345	199	235	271	307
					Houston	610	271	307	344	380
Miami	0.792	694	549.07	192.17	New York	1145	393	429	465	581
					Miami	10	54	90	125	163
					New Orleans	852	303	339	375	411
					Houston	1052	363	399	435	471
New Orleans	0.630	552	416.76	152.87	Miami	852	371	407	444	480
					New Orleans	58	91	127	164	200
					Houston	403	252	288	324	360
Brownsville	0.635	557	440.22	154.08	Houston	357	227	263	299	335
Puerto Rico	0.785	688	544.21	190.47	New York	1609	482	518	554	590
					Miami	1104	382	418	454	490
					New Orleans	1772	509	545	581	617
					Houston	1972	561	597	633	669
Hawaii	0.812	711	562.93	197.03	Los Angeles	2953	742	778	814	850
Brazil	0.793	695	549.76	192.42	New York	4253	1022	1058	1094	1130
					Miami	3974	960	996	1032	1068
					New Orleans	4829	1147	1184	1220	1256
					Houston	4966	1170	1206	1243	1279

* 100 MW plant using busbar costs of 10, 20, 30, and 40 mills/kWhr. Electricity costs are for baseload.

† No optimistic assumptions were made for ammonia.

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Table ES-7. OTEC ELECTRIC POWER* DELIVERED TO DESTINATION BUSBAR VIA LITHIUM/LITHIUM HYDROXIDE BRIDGE (1976 $/kWhr)

OTEC Site	Net Capacity Factor	Annual Electricity Production, 10^6 kWhr	Annual Lithium Production, 10^3 tons	Annual Electricity Delivery, 10^6 kWhr	Destination	Distance, Statute Miles	Delivered Electricity Cost,** Conservative Assumptions (mills/kWhr)				Delivered Electricity Cost,** Optimistic Assumptions (mills/kWhr)			
Key West	0.750	657	49.17	408	New York	1380	80	96	112	128	67	83	99	115
					Miami	250	57	74	90	106	44	60	77	93
					New Orleans	600	64	80	96	112	51	67	83	99
					Houston	800	68	84	100	116	55	71	87	103
West Florida	0.720	611	47.40	391	Miami	515	64	80	96	112	50	66	82	98
					New Orleans	345	61	77	93	109	47	55	79	95
					Houston	610	66	82	99	114	52	68	84	101
Miami	0.792	694	52.14	431	New York	1145	73	89	105	121	61	77	93	109
					Miami	10	54	70	86	102	41	57	74	90
					New Orleans	850	66	82	99	115	54	70	86	102
					Houston	1050	71	87	103	119	59	75	91	107
New Orleans	0.630	552	41.47	343	Miami	850	79	95	111	128	64	80	96	112
					New Orleans	60	64	80	96	112	48	65	81	97
					Houston	400	68	84	100	117	53	69	85	101
Brownsville	0.635	556	41.80	345	Houston	355	67	83	99	109	51	67	83	94
Puerto Rico	0.785	688	51.68	427	New York	1610	82	98	113	130	70	86	100	118
					Miami	1105	73	89	105	121	60	76	92	108
					New Orleans	1770	85	101	118	134	73	89	105	121
					Houston	1970	89	105	121	137	76	92	108	125
Hawaii	0.812	711	51.46	442	Los Angeles	2955	104	120	136	152	92	108	124	140
Brazil	0.793	695	52.20	431	New York	4255	129	145	161	177	117	133	149	165
					Miami	3975	127	143	159	175	114	130	147	163
					New Orleans	4810	142	158	174	190	129	145	162	178
					Houston	4965	146	162	179	195	134	150	166	182

* 100 MW plant.
10, 20, 30, 40 mills/kWhr OTEC busbar costs.

** Base load.

The economics of each of these carriers were analyzed to determine the potential penetration in a number of markets. These markets are given in Table ES-8.

Table ES-8. ENERGY MARKETS EXAMINED

Carrier	Market
Lithium/Lithium Hydroxide	Electricity Generation - Baseload Electricity Generation - Peaking
Hydrogen	Electricity Generation - Baseload Electricity Generation - Peaking
	Aircraft Fuel Industrial Fuel Domestic Fuel
Ammonia	Electricity Generation - Peaking
	Fertilizer - as Ammonia Fertilizer - as Ammonium Nitrate
Molten Salts	Electricity Generation - Peaking
	Process Heat

The ability of these carriers to compete in these markets was determined based upon the comparison of their costs with alternative energy sources. These sources included both conventional and new technologies, i.e., conventional natural gas, coal- and nuclear-based electricity generation, OPEC natural gas (LNG), coal gasification, high-performance batteries, and thermal media storage (molten salts). If the OTEC carriers were considered competitive, the size of the marketplace and other pertinent factors were examined to determine the potential market penetration for the carriers. The other pertinent factors included such influences as the date and location when the fuel is needed (hydrogen aircraft), the stability of prices in the industry (ammonia fertilizer), and the management risks perceived in using the carrier as an energy source (molten salts for process heat).

Of the carriers, only ammonia appears promising, and then only as a fertilizer or a fertilizer feedstock. OTEC ammonia will be competing heavily against ammonia from coal. Because the OTEC platform can produce electricity at 10 mills/kWhr, OTEC ammonia could sell 0.8 million short tons/year (at 100%)

by 1985 and 3.5 million tons by 2000. If the OTEC electric cost is 20 mills/kWhr, no market penetration is predicted for 1985 and only 1.2 million tons by 2000. OTEC-based ammonium nitrate sales would closely match, on a percentage of market basis, those for ammonia. These can not be considered to be additive because the overall ammonia estimates include the ammonia which would be used as a feedstock for ammonium hydroxide.

The prospects of OTEC ammonia for the electrical peaking market are nonexistent. Competing technologies are too strong.

Hydrogen has some limited prospects if ideal conditions are met. The OTEC electricity must be under 20 mills/kWhr in all cases and under 10 mills/kWhr in most. The transportation distance must be under 100 miles to be competitive as an aircraft fuel, and under 25 miles to be competitive as a domestic or industrial fuel. Unfortunately, because of the distances, these markets are limited to the Miami/Miami site-destination combination.* Therefore, under optimum conditions, the maximum market penetration for hydrogen in 2000 would be 23 to 38 trillion Btu as an industrial or domestic fuel, and 13 trillion Btu as an aircraft fuel. Because of competing technologies, hydrogen will not be in competition with either the electrical baseload or the electrical peaking markets. The major problem with the hydrogen economics is that the costs of transporting it are large on a cost/Btu-mile basis; at distances over 400 miles, it must be liquified.

Molten salts appear to have economics with the same constraints as hydrogen. The cost of OTEC electricity must be low, and the transportation distances must be short. Predicted market penetration for process heat or peaking electricity was negligible. As a source for process heat, molten salts require too many management risks in return for the marginally competitive costs. As a source of peaking electricity, molten salts would be competing against the very technology that would make it possible, a thermal media system, which did not have to be moved and which could be powered with less expensive off-peak utility power.

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* There will be no hydrogen fuel requirement in New Orleans until after the year 2000. For further explanation, see Section 3.2.

The overall results of these studies for hydrogen, lithium/lithium hydroxide, ammonia, and molten salts are negative. But before becoming disillusioned, one must remember that the results were constrained by the assumptions of the size of the OTEC and carrier production plants and the resulting inefficiencies in transportation economics. A rough study done at IGT has indicated that transportation costs could be reduced by as much as 25% in some cases if the OTEC plants were sized at 500 MW or more, and clustered to provide total nominal capacity in excess of 1500 MW. A more detailed study of the effects of increased plant and cluster capacities would be worthwhile.

Table ES-9 consolidates the potential market penetration for OTEC energy for the different carriers and markets considered in terms of total OTEC generating capacity required.

Table ES-9. POTENTIAL MARKET PENETRATION FOR OTEC ENERGY IN TERMS OF INSTALLED OTEC CAPACITY (Nominal; in Gigawatts)

	Market	Carrier	OTEC Busbar Costs Mills/kWhr	Installed OTEC Capacity 1990 (GW)	Installed OTEC Capacity 2000 (GW)
I.	Electrical Generation				
	Baseload	Lithium	< 11	0	0
			11-20	0	0
			21-30	0	0
			31-40	0	0
		Hydrogen	< 11	0	0
			11-20	0	0
			21-30	0	0
			31-40	0	0
	Peaking	Lithium†	< 11	0	0
			11-20	0	0
			21-30	0	0
			31-40	0	0
		Hydrogen	< 11	0	0
			11-20	0	0
			21-30	0	0
			31-40	0	0
		Ammonia	< 11	0	0
			11-20	0	0
			21-30	0	0
			31-40	0	0
		Molten Salts	< 11	0	0
			11-20	0	0
			21-30	0	0
			31-40	0	0
II.	Fertilizers				
	Ammonia and Fertilizers Feedstocks	Ammonia	< 11	1.5	4.7
			11-20	0	2.2
			21-30	0	0
			31-40	0	0
	Ammonium Nitrate*	Ammonia	< 11	0.2*	0.7*
			11-20	0	0.2
			21-30	0	0
			31-40	0	0
III.	Hydrogen Aircraft Fuel	Hydrogen	< 11	0	0.7
			11-20	0	0
			21-30	0	0
			31-40	0	0
IV.	Industrial and Domestic Fuel	Hydrogen	< 11	0	0.2
			11-20	0	0
			21-30	0	0
			31-40	0	0
V.	Process Heat	Molten Salts	< 11	0	0
			11-20	0	0
			21-30	0	0
			31-40	0	0
	Total		< 11	1.5	5.6
			11-20	0	2.2
			21-30	0	0
			31-40	0	0

*The ammonia requirement for ammonia nitrate is included in the ammonia and fertilizer feedstocks figures.

[illegible]

†Based on high-demand, conservative cost case.

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1. INTRODUCTION

This is the final report with the General Electric Company-TEMPO (GE-TEMPO) under Subcontract No. 29412. The purpose of this subcontract was to examine the economics of using each of three energy carriers — ammonia, hydrogen, and molten salts — to transport OTEC-generated energy to shore to add to the total U.S. supply of energy during the period 1985 to 2000. Onshore, these carriers were either used to generate electricity or sold as an energy-intensive commodity product. The economics under examination were total delivered costs, costs of competing energy forms and sources, and projected market penetration.

This subcontract was performed in conjunction with GE-TEMPO Subcontract No. 29343 (IGT Project 9518), which examined the economics of using a lithium/lithium hydroxide carrier to transport electricity. The final report for Subcontract No. 29343 was issued on December 22, 1977[1] and a revised version of this is provided here as Appendix A-1. The general purpose of both subcontracts was to provide the Department of Energy (DOE), through GE-TEMPO, with realistic estimates of the ability of OTEC platforms, in a preliminary stage, to use four types of energy carriers to provide competitive future energy sources for the United States. The energy delivered could be in the form of electricity, heat, fuel, or an energy-intensive commodity. The constraints for the examination were the following:

- The energy carriers would be hydrogen, ammonia, lithium/lithium hydroxide, and molten salts.
- The OTEC plants would be advanced long range improved technology (ALRIT) incorporating reasonably predictable technology advances from the current state-of-the-art.
- The carriers used would be manufactured/processed onboard the platform or in vessels moored next to the OTEC platform, also using advanced long range improved technologies.
- The OTEC platforms would have a nominal 100-MW capacity.
- The OTEC platforms would be considered as single units rather than in clusters to approximate the case where they are just introduced.
- The economics would be considered for eight sites designated by GE-TEMPO. Each site would have a "seasonal" factor, which would affect the total quantity of OTEC electricity produced.[2]
- The OTEC energy system would include onboard generation of electricity, onboard conversion to the enbergy carrier, transportation to shore, terminalling, conversion to electricity (optional), and return of the "used" carrier (molten salts, lithium hydroxide) to the OTEC platform.

- The OTEC platform would be assumed to be producing electricity at 10, 20, 30, and 40 mills/kWhr after all costs and outputs were taken into consideration.

The major assumptions relate to the OTEC plant size, OTEC plant type (grazing vs. anchored), the density of clustering of OTEC plants, the shipping methodology and financing, and the seasonal and locational effects on electricity production. By assuming that single 100-MW units will be in operation, rather than multiple clusters of larger sized units, considerable impacts result on the energy-delivery economics. First, scale economics in the production of the energy carriers will be lower than with the larger capacity plants. Second, the quantity of an energy carrier from the 100-MW plants is too small to warrant full-sized commercial vessels. This leaves barges as the principal, and relatively more expensive, mode for transporting these carriers to port. Even with barges, there will be significant inefficiencies as the seasonal* ΔT variations affect the quantities of carrier shipped. The net result is higher energy carrier costs at the plant and substantially higher shipping costs than if the study dealt with clusters of large-scale OTEC plants.

However, IGT felt that the decisions to invest in the first commercial OTEC plants will be made for 100-MW units on the basis of the results from the 10 and 20-MW pilots and projections for the 100-MW plants. Further, investments in the second and following 100-MW plants will be based on the economics of the first plant. This situation leads to a potential "catch 22" in the decision-making process, i.e., OTEC will be the most economically justifiable in clusters of large-scale plants; however, the OTEC decisions will be based on the less economical 100-MW plants. In IGT's judgment, it was clearly more prudent to make our analysis of OTEC economics based on the plant size level on which we believe the critical early decisions would be made.

In the long run, it is likely that owners of OTEC plants will invest in clusters (4 or more) of grazing 350 to 500-MW OTEC plants, but a scale-up of 35 to 1 and a jump from a pilot plant configuration to a large-scale commercial configuration is unlikely to occur within the 1980 to 2000 time frame of this study. If a much longer planning horizon can be allowed, it would be prudent to examine in detail the economic sensitivities of the size and location parameters that were fixed in this study.

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* The seasonal and locational effects on electricity were specified by GE-TEMPO. These are described in detail in the main body of the report.

The specific task areas for Subcontract No. 29412 were the following:

1. IGT shall identify market potential for ammonia as an energy-intensive industry.

2. IGT shall examine the costs of supplying ammonia as fertilizer and OTEC hydrogen as an aircraft fuel to the U.S. market. The cost of these OTEC options shall be compared in the year 2000 time frame with estimated competitive costs of other sources of energy (e.g., coal, OPEC natural gas, and biomass), to supply these markets. Market penetration of OTEC ammonia and hydrogen shall be estimated.

3. IGT will study the costs of supplying OTEC products other than lithium-related materials to the electrical peaking market with the associated comparison with other options and market penetration projections. These OTEC products shall include cryogenic hydrogen, liquid ammonia, and molten salts.

4. IGT shall study the costs of ammonium nitrate for application as a fertilizer with the associated comparison, with costs of other competitive sources of energy and market penetration.

5. IGT shall study the costs for supplying OTEC hydrogen for application as a base-load (central station and dispersed fuel cell) electricity and industrial and domestic fuels with the associated comparison of costs of other competitive sources of energy and estimates of market penetration.

6. IGT shall examine the costs of supplying OTEC heat for process applications via a thermal bridge to shore and the associated cost comparisons and market penetration estimates.

For streamlining purposes, we have divided this report into two sections. The first section describes the methodology, assumptions, and results of our calculations of the delivered costs 1) of commodity, hydrogen, ammonia and process heat through molten salts, and 2) of electricity using hydrogen, ammonia and molten salt energy carriers. The second section presents the results of the above tasks in terms of competitive costs, market penetration, and/or market potential.

Throughout these subcontracts, we found that the figures for markets and fuel costs not associated with electricity generation were more available and reliable for the year 1985 than 1990. Given this, for the non-electrical markets, we have calculated the market penetration for 1985 and then extrapolated to 1990, the year the OTEC platforms are expected to be commercially available.

2. PRODUCT COSTS

To determine the level of penetration for each of the OTEC products, we used what is considered to be the most straightforward methodology possible; to determine the OTEC product costs, we used the same methodology incorporated by IGT in previous investigations for DOE. These are described in detail in the IGT studies entitled "An Optimization Study of OTEC Delivery Systems Based on Chemical-Energy Carriers,"[3] and "Alternative Energy Transmission Systems for OTEC Plants."[4] In most cases, we used published market predictions for the size, characteristics, and competitive economics of the different markets under consideration. We also developed specific methodologies for those cases where we had special expertise or where standard sources were not available or reliable. The market penetration methodology used was based upon a comparison of projected costs for the OTEC carriers with those for competitive technologies.

2.1 OTEC Electric Power Production

The OTEC Electric Power Production study did not attempt to calculate the specific performance of a given OTEC design. Rather, IGT began with the assumption, as requested by GE-TEMPO, that after all seasonality and operating factors were taken into account, the OTEC platform would produce onboard busbar electricity at a net cost in the range of 10 to 40 mills/kWhr. As a result, the cost estimates are based upon net platform electricity costs at 10, 20, 30, and 40 mills/kWhr. The platform capacity chosen had a nominal capacity of 100 MW, assuming that the platforms operated 90% of the time, with 876 hours per year for maintenance and repair downtime. GE-TEMPO provided eight possible OTEC site locations, but because of seasonal variations in the temperature differential, each site required a Seasonal Variation Capacity Factor Correction (also provided by GE-TEMPO).[2] When both the 90% operating factor and the Seasonal Variation Capacity Factor Correction were taken into account, the result was a net capacity factor. This net capacity factor was then used to determine the total quantity of electricity produced by the OTEC platforms in each site. Because of the approach of using a range of costs, it was assumed that the net capacity factor did not affect the cost per kilowatt hour for the platform. The effect of this net capacity factor is given in Table 1.

In this study, an OTEC plant size of 100 MW was assumed. This is the maximum rated output under the most favorable design point conditions. The net capacity factor converts this to an annual average output figure.

Table 1. ANNUAL OTEC ELECTRICITY PRODUCED FROM A SINGLE 100-MW PLATFORM

Location	Distance To Shore, nautical miles	Nominal Annual Electric Production, 10^6 kWhr	Operating Factor, %	Seasonal Variation Capacity Factor Correction, %	Net Capacity Factor, %	Net Annual Electric Production, 10^6 kWhr
		(a)	(b)	(c)	(b)X(c)	(a)X(b)X(c)
Key West	40	876	90	83.41	75.0	657
West Florida	160	876	90	30.00	72.0	630
Miami	< 10	876	90	88.16	79.2	694
New Orleans	50	876	90	70.29	63.0	552
Brownsville	100	876	90	70.80	63.5	556
Puerto Rico	3	876	90	87.25	78.5	688
Hawaii	1	876	90	90.25	81.2	711
Brazil	>200	876	90	88.37	79.3	695

2.2 OTEC Carrier Production

The production of the different energy carriers is assumed to take place either onboard the OTEC platform, as in the case of hydrogen and ammonia, or onboard an ocean-going vessel moored to the platform, as in the case of molten salts. Because the net capacity factor is based upon seasonal variations in electric output, the carrier production facilities must be sized to accomodate an electricity production load at 100% of the nominal capacity. With each carrier, we have used an advanced long range improved technology (ALRIT) production scheme, which we believe will be available in the mid-1980's. For the hydrogen carrier, we calculated the costs (in 1976 dollars) of both gaseous and liquid hydrogen and found that, for over-water shipping distances of more than 400 statute miles, it is cheaper to ship hydrogen in a liquid form rather than in a gaseous form in terms of total cost per unit of energy of hydrogen delivered. For ammonia, we calculated the costs for the production of liquid ammonia onboard the OTEC platform. For molten salts, the production of heat through electrical resistance takes place onboard the shipping vessels. As a result, the production costs of molten-salt heat are integral to the shipping costs and are treated in that section.

2.2.1 Gaseous Hydrogen Production

The production of gaseous hydrogen is based upon ALRIT technologies and requires the following major components: an acyclic generator, a solid-polymer-electrolyte electrolyzer,[2] a standard a-c generator, and a desalinizer. The capacity of the production systems, operating to meet the OTEC plant running at 100% of nominal capacity, with a 100-MW power source, is 57 tons per day of gaseous hydrogen. The actual production per OTEC platform of gaseous hydrogen at each site is shown in Table 2. The investment required in the production system for gaseous hydrogen will be approximately $7.1 million. The total annual costs for gaseous hydrogen are shown in Table 3. These costs are assumed constant regardless of the actual platform site chosen.

2.2.2 Liquid Hydrogen Production

The production of liquid hydrogen begins with the same major components as gaseous hydrogen but adds a liquefaction section. The capacity of this production system operating to meet the OTEC plant running at 100% of nominal

Table 2. ANNUAL HYDROGEN PRODUCTION PER PLATFORM; 100-MW OTEC SITE LOCATIONS (10^3 tons/year)

Site Location	Net Capacity Factor, %	Annual Electric Production, kWhr X 10^6	Annual Gaseous Hydrogen Production, tons X 10^3	Annual Liquid Hydrogen Production, tons X 10^3
Key West	75.0	657	15.6	12.3
West Florida	72.0	630	15.0	11.8
Miami	79.2	694	16.5	13.0
New Orleans	63.0	552	13.1	10.3
Brownsville	63.5	556	13.2	10.4
Puerto Rico*	78.5	688	16.3	12.9
Hawaii*	81.2	711	16.9	13.3
Brazil*	79.3	695	16.5	13.0

* Because the shipping distances from Puerto Rico, Hawaii, and Brazil are all over 400 miles, no gaseous hydrogen is shipped.

Table 3. ANNUAL GASEOUS AND LIQUID HYDROGEN PRODUCTION COSTS; 100-MW OTEC SITE LOCATIONS (1976 Dollars X 10^6)

	Annual Production Costs	
Cost Description	Gaseous Hydrogen, \$ X 10^6	Liquid Hydrogen, \$ X 10^6
Fixed Charges: 18.6% of Investment	1.32	5.14
Utilities, Chemicals: 1% of Investment	0.07	0.27
Maintenance: 2% of Investment	0.14	0.55
Operating Labor	0.47	0.76
Supervision	0.09	0.16
Overhead and G&A	0.38	0.72
Total	2.47	7.60

capacity is 45 tons per day. The actual production of liquid hydrogen per platform at the different sites is given in Table 2. The investment required in the production system will be approximately $27.7 million. The total annual costs for liquid hydrogen are shown in Table 3. These costs are assumed constant regardless of the actual platform site chosen.

2.2.3 Liquid Ammonia Production

The production of liquid ammonia starts with the same major components as the gaseous hydrogen plant but adds an air-separator plant and ammonia-synthesis system. The production capacity of the resulting system, when fed by a 100-MW OTEC platform running at 100% of nominal capacity is 282 tons per day.* The actual production of liquid ammonia per OTEC platform for each site is shown in Table 4. The shipment of ammonia in a gaseous form was considered. However, the ease with which ammonia is liquefied, the inherently low transportation costs by vessel, and the normal end requirement for ammonia to be in a liquid form swing the economics strongly toward liquefaction. The investment required in the production system for ammonia will be approximately $20.1 million. The total annual costs for liquid ammonia are shown in Table 5. These costs are assumed constant regardless of the actual platform site chosen.

Table 4. ANNUAL LIQUID AMMONIA PRODUCTION PER PLATFORM; 100-MW OTEC SITE LOCATIONS (10^3 tons/year)

Site Location	Net Capacity Factor, %	Annual Electric Production, kWhr X 10^6	Annual Liquid Ammonia Production, tons X 10^3
Key West	75.0	657	77.2
West Florida	72.0	630	74.1
Miami	79.2	694	81.5
New Orleans	63.0	552	64.8
Brownsville	63.5	556	65.4
Puerto Rico	78.5	688	80.8
Hawaii	81.2	711	83.6
Brazil	79.3	695	81.6

* The apparent difference in tonnage between the hydrogen and ammonia systems is explained by the higher molecular weight of nitrogen.

Table 5. ANNUAL LIQUID AMMONIA PRODUCTION COSTS; 100-MW OTEC SITE LOCATIONS (1976 Dollars X 10^6)

Cost Description	Annual Production Cost, $ X 10^6
Fixed Charges: 18.6% of Investment	3.74
Utilities, Chemicals: 1% of Investment	0.20
Maintenance: 2% of Investment	0.40
Operating Labor	0.57
Supervision	0.11
Overhead and G&A	0.53
Total	5.55

2.2.4 Molten Salts Production

The production of heat in molten salts is totally integrated into the transportation costs. Each vessel has an extensive, built-in resistance heating system. These costs are discussed as part of the transportation costs. The molten salt technology chosen was HITEC. In our previous investigations, HITEC consistently produced the lowest cost per Btu of all the thermal storage media investigated.

2.3 OTEC Energy Carrier Transportation

The transportation costs for the different energy carriers are dependent upon the type of carrier, the distance covered, and the form of transportation used. The types of carriers are gaseous hydrogen, liquid hydrogen, liquid ammonia, and molten salts. The distance covered was dependent upon the platform locations and the ultimate delivery ports. (These ports were provided by GE-TEMPO.[2]) Not all ports were considered to be reasonable destinations for each platform location; Los Angeles was considered too far from the East Coast, Gulf Coast, Caribbean, and Brazilian sites for economical transportation. Similarly, the Hawaiian site was considered too far from the Gulf and East Coast ports. Additionally, a number of combinations for certain ports were discarded because lower distances and higher net capacity factors were available from other OTEC sites. The resulting site-port combinations that were considered are given in Table 6. Considering the excessive distances to any U.S.

Table 6. OTEC SITE-DESTINATION COMBINATIONS
(Approximate Distances, Statute Miles)

OTEC Site	Net Capacity Factor, %	Port Destination	Distance, statute miles
Key West	75.0	New York	1380
		Miami	250
		New Orleans	600
		Houston	800
Florida, West Coast	72.0	Miami	515
		New Orleans	345
		Houston	610
Miami	79.2	New York	1145
		Miami	10
		New Orleans	850
		Houston	1050
New Orleans	63.0	Miami	850
		New Orleans	60
		Houston	400
Brownsville (Texas)	63.5	Houston	355
Puerto Rico	78.5	New York	1610
		Miami	1105
		New Orleans	1770
		Houston	1970
Hawaii	81.2	Los Angeles	2955
Brazil	79.3	New York	4250
		Miami	3970
		New Orleans	4830
		Houston	4970

port and the comparable net capacity factor (79.3% for Brazil vs. 79.2% for Miami or 78.5% for Puerto Rico), Brazil appears to be an unlikely prospect unless the bus-bar costs of electricity are extremely low compared with other sites.

The forms of transportation used were pipelines for gaseous hydrogen, ocean-going barge and tug combinations for liquid hydrogen and ammonia, and a specially retrofitted ship for molten salts. A previous economic study[3] showed that barge transportation of liquid hydrogen "breaks even" with pipeline transportation of gaseous hydrogen on a per Btu basis at about 100 miles. However, when shipping losses, liquefaction and gasification losses and costs, and terminalling costs are taken into account, the break even point in terms of total cost of delivered hydrogen gas takes place in the 350 to 450 mile range, depending upon the cost of gas. (See Figure 1.)

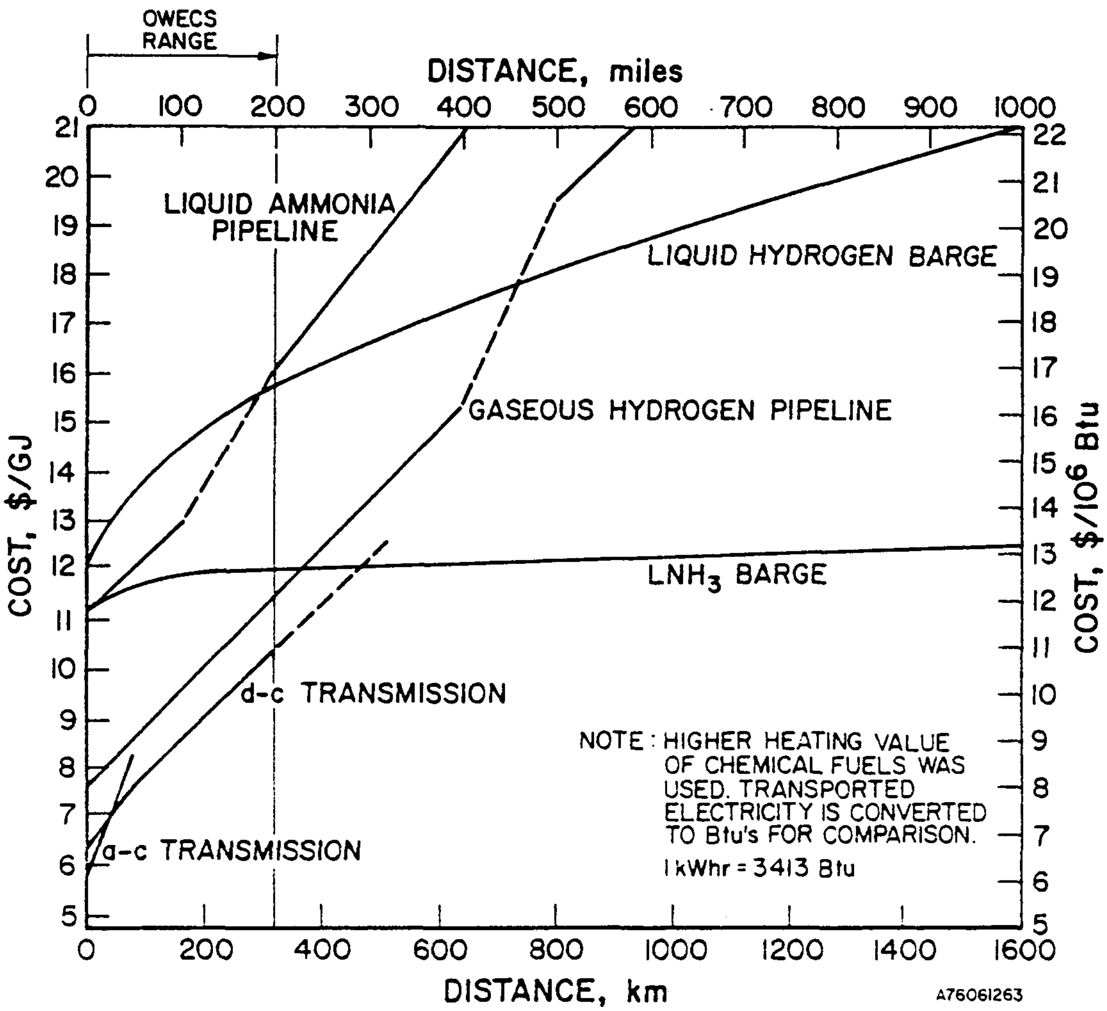

Figure 1. DELIVERED ENERGY TRANSPORTATION COST COMPARISON
(OTEC Shaftpower Cost 20 mills/kWhr; 100-MW Plant)

The barge transportation costs for each energy carrier were calculated individually for each OTEC site-destination combination. In the case of liquid hydrogen, the percentage of boil-off was calculated to be 3.2% of total hydrogen transported distance for distances less than 1800 miles. For distances greater than that, the boil-off was calculated to range from 3.2% to 13.1% (5000 miles). The actual barges were sized at 15,000, 30,000, or 60,000 barrel capacities for liquid hydrogen and ammonia. Because of the uncertainty in design for hydrogen transportation, the capital costs of these barges were determined on both conservative ($600/bbl) and optimistic ($350/bbl) bases over the range of barge sizes assumed. Ammonia barge economics are well known, so only one estimate is given which shows a reduction in unit cost with an increase in barge size. Tables 7 and 8 show the total barge and tug capital costs for liquid hydrogen and liquid ammonia. The barge costs include any speciality storage tanks and equipment required for the energy carrier.

Table 7. BARGE AND TUG CAPITAL COSTS FOR LIQUID HYDROGEN (1976 Dollars X 10^6)

Barge Capacity, bbl X 10^3	Optimistic, $	Conservative, $	Tug Shaft Horsepower, shp	Tug Cost, $ X 10^6
15	5.25	9	1000	0.90
30	10.50	18	1500	1.25
60	21.00	36	2400	2.00

Table 8. BARGE AND TUG CAPITAL COSTS FOR LIQUID AMMONIA (1976 Dollars X 10^6)

Barge Capacity, bbl X 10^3	Estimated Barge Cost, $ X 10^6	Tug Shaft Horsepower, shp	Tug Cost, $ X 10^6
15	2.2	1000	0.90
30	3.5	1500	1.25
60	6.2	2400	2.00

The costs for molten salt transportation are more complex. Because each of the ships is used for both energy transportation and energy storage (during charging and discharging at the platform and ports, respectively), two extra ships are needed for each platform. Ship capacity and total number of ships are calculated based upon distance and nominal electrical output of the OTEC plant. The ship costs are estimated at $150 per ton of HITEC electrical capacity. The total costs for HITEC and ships were estimated at about $506 per ton of HITEC.[4]

The annual transportation costs were then calculated for each energy carrier and for each OTEC site-destination combination. Terminalling costs were also calculated for each combination and are presented in Table 9. The transportation and terminalling costs include all fixed capital charges, maintenance costs, labor cost, fuel costs, etc.

By totalling the annual costs of electricity (at 10, 20, 30, and 40 mills per kWhr), the carrier production, the transportation, the terminalling, and the annual costs for the delivered energy carriers are obtained. That total divided by the total quantity of carrier delivered yields the annual cost per unit of delivered carrier. The results of these calculations are given in Tables 10, 11, and 12 for hydrogen, ammonia, and molten salts, respectively. Only in the case of ammonia does further processing occur onshore for ammonium nitrate production. To manufacture one ton of ammonium nitrate, 0.45 ton of ammonia is required. Figure 2 shows the cost of ammonium nitrate as a function of liquid ammonia cost for production facilities ranging from 600 to 3000 tons per day of ammonium nitrate. The nominal output of an OTEC platform is 282 tons per day. Thus, a single 100-MW OTEC platform would require an ammonium nitrate plant of approximately 600 tons per day capacity. For 10 mills/kWhr OTEC electricity, the ammonium nitrate would cost from $125/ton to $260/ton (in 1976 dollars), depending upon the distance between the site and shore. The unit costs of the delivered hydrogen, ammonia, ammonium nitrate, and molten salts will be those used to determine potential market penetration.

To reconvert these carriers to electricity, different types of generating equipment are used. For hydrogen, a gas turbine is used with an a-c generator system; for ammonia, an ammonia-air fuel cell is used; for molten salts, a heat engine is used. When the hydrogen is delivered in a liquid form, it must be gasified prior to using the fuel cell. The annual costs for generating electricity for each carrier are shown in Table 13. These costs are then added to the delivered carrier costs. The cost per kWhr is then calculated based upon total electricity produced. These results are shown in Tables 14, 15, and 16 for hydrogen, ammonia, and molten salts, respectively. It will be these costs that are used to determine the ability of OTEC energy to penetrate the different electricity markets.

Table 9. OTEC ENERGY CARRIERS ANNUAL TRANSPORTATION AND TERMINALLING COSTS (1976 Dollars)

OTEC Site	Port Destination	Distance, Statute Miles	Annual Hydrogen Costs: Transportation, Conservative, $ X 10^6	Annual Hydrogen Costs: Transportation, Optimistic, $ X 10^6	Annual Hydrogen Costs: Terminalling, $ X 10^6	Annual Ammonia Costs: Transportation, $ X 10^6	Annual Ammonia Costs: Terminalling, $ X 10^6	Annual Molten Salts Costs, Transportation, $ X 10^6	Annual Molten Salts Costs, Terminalling $ X 10^6
Key West	New York	1380	12.64	9.13	4.24	2.95	0.27	74.72	†
	Miami	250	11.89*	11.89*	*	1.52	0.20	19.38	†
	New Orleans	600	9.62	6.69	2.36	1.91	0.22	38.95	†
	Houston	800	12.42	8.70	4.24	2.13	0.23	46.69	†
Florida, West Coast	Miami	515	8.15	5.87	2.70	1.74	0.21	33.00	†
	New Orleans	345	15.73*	15.73*	*	1.56	0.20	26.74	†
	Houston	610	9.62	6.69	2.36	1.91	0.22	39.40	†
Miami	New York	1145	12.72	8.87	4.24	2.[illegible]0	0.26	66.86	†
	Miami	10	1.44*	1.44*	*	1.44	0.20	1.80	†
	New Orleans	850	12.44	8.70	4.24	2.11	0.22	49.53	†
	Houston	1050	12.63	8.80	4.24	2.45	0.24	61.05	†
New Orleans	Miami	850	12.44	8.70	4.24	2.11	0.22	49.53	†
	New Orleans	60	2.69*	2.69*	*	1.47	0.20	6.74	†
	Houston	400	7.18	5.05	2.28	1.56	0.20	31.24	†
Brownsville (Texas)	Houston	355	15.73	15.73	*	1.56	0.20	31.24	†
Puerto Rico	New York	1610	12.74	8,99	4.24	3.15	0.28	83.15	†
	Miami	1105	12.56	8.85	4.24	2.52	0.25	64.18	†
	New Orleans	1770	12.82	9.08	4.24	3.19	0.28	88.30	†
	Houston	1970	12.96	9.21	4.24	3.23	0.28	98.27	†
Hawaii	Los Angeles	2955	20.09	14.46	4.24	3.50	0.37	137.35	†
Brazil	New York	4250	29.81	21.34	4.24	5.71	0.37	188.00	†
	Miami	3970	26.08	18.58	4.24	5.65	0.37	176.00	†
	New Orleans	4830	3265	23.27	4.24	6.58	0.37	212.1[illegible]	†
	Houston	4970	32.77	23.39	4.24	6.60	0.37	216.[illegible]	†

* Hydrogen gas transportation.

† Included in the transportation costs.

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Table 10. OTEC PRODUCED LIQUID HYDROGEN DELIVERED TO VARIOUS SITES ($/10^6 Btu, 1976 Dollars)

OTEC Site	Net Capacity Factor	Annual Electricity Production, 10^6 kWhr	Annual Liquid Hydrogen Production, 10^3 Tons†	Annual Liquid Hydrogen Delivery, 10^3 Tons	Destination	Distance, Statute Miles	Delivered Cost of Liquid Hydrogen, Conservative Assumptions ($/10^6 Btu): 10 Mills	20 Mills	30 Mills	40 Mills	Delivered Cost of Liquid Hydrogen, Optimistic Assumptions ($/10^6 Btu): 10 Mills	20 Mills	30 Mills	40 Mills
Key West	0.750	657	12.31	11.92	New York	1377	21.32	25.83	30.34	34.85	18.90	23.42	27.93	32.44
			15.60*	15.60	Miami	250	10.74	14.42	17.87	21.32	10.74	14.42	17.87	21.32
			12.31	11.92	New Orleans	603	17.89	22.40	26.91	31.42	15.94	20.45	24.96	29.47
			12.31	11.92	Houston	803	21.16	25.67	30.18	34.35	18.68	23.15	27.66	32.17
West Florida	0.720	631	11.82	11.44	Miami	516	17.71	22.22	26.74	31.25	16.06	20.59	25.10	29.62
			14.97*	14.97	New Orleans	345	13.40	16.85	20.05	23.75	13.40	16.85	20.05	23.75
			11.82	11.82	Houston	610	18.52	23.11	27.55	32.06	16.42	21.00	25.45	29.96
Miami	0.792	694	13.00	12.59	New York	1145	20.47	24.98	29.49	34.00	18.04	22.55	27.06	31.57
			16.47*	16.47	Miami	10	5.39	8.89	12.29	15.51	5.39	8.89	12.29	15.51
			13.00	12.59	New Orleans	852	20.29	24.80	29.31	33.82	17.86	22.37	26.88	31.39
			13.00	12.59	Houston	1052	20.42	24.93	29.44	33.95	17.98	22.49	27.00	31.52
New Orleans	0.630	552	10.34	10.01	Miami	852	24.36	28.87	33.39	37.90	21.30	25.81	24.79	34.84
			13.10*	13.10	New Orleans	58	6.67	10.12	18.57	17.02	6.67	10.12	18.57	17.02
			10.34	10.01	Houston	403	18.46	22.97	27.48	30.99	16.72	21.23	25.74	30.26
Brownsville	0.635	557	13.21*	13.21	Houston	357	14.72	18.16	21.61	24.93	14.72	18.16	21.61	24.93
Puerto Rico	0.785	689	12.89	12.47	New York	1609	20.63	25.15	29.66	34.19	18.18	22.70	27.21	30.73
			12.89	12.47	Miami	1104	20.53	25.04	29.56	34.07	18.06	22.57	27.10	31.60
			12.89	12.47	New Orleans	1772	20.70	25.21	29.73	34.37	18.24	22.75	27.26	31.78
			12.89	12.21	Houston	1972	21.23	25.30	30.45	34.33	18.72	22.84	27.94	31.87
Hawaii	0.812	711	13.33	12.31	Los Angeles	2953	25.95	30.68	35.40	40.13	22.21	26.93	31.66	36.38
Brazil	0.793	695	13.02	11.49	New York	4253	34.61	39.56	44.51	49.46	28.58	33.53	38.48	43.43
			13.02	11.67	Miami	3974	31.46	36.34	41.21	46.08	26.20	31.10	35.95	40.82
			13.02	11.31	New Orleans	4829	37.22	42.25	47.27	52.30	30.43	35.46	40.49	45.52
			13.02	11.31	Houston	4966	37.31	42.33	48.95	52.39	30.52	35.54	40.57	45.60

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* Gaseous hydrogen.

† All "tons" in this report are "short tons."

Table 11. OTEC PRODUCED LIQUID AMMONIA DELIVERED TO VARIOUS SITES ($/ton, 1976 Dollars)

OTEC Site	Net Capacity Factor	Annual Electricity Production, 10^6 kWh$_e$	Annual Liquid Ammonia Production, 10^3 tons	Annual Liquid Ammonia Delivery, 10^3 tons	Destination	Distance, statute miles	Delivered Costs of Liquid Ammonia: 10 Mills ($/ton)	20 Mills ($/ton)	30 Mills ($/ton)	40 Mills ($/ton)
Key West	0.750	657	77.20	77.20	New York	1377	199	284	369	454
					Miami	250	179	264	349	435
					New Orleans	603	185	270	355	440
					Houston	803	188	273	358	443
West Florida	0.720	631	74.11	74.11	Miami	516	186	272	357	442
					New Orleans	345	184	269	354	439
					Houston	610	189	274	359	444
Miami	0.792	694	81.52	81.52	New York	1145	188	273	359	444
					Miami	10	173	258	344	429
					New Orleans	852	182	267	352	437
					Houston	1052	186	271	356	442
New Orleans	0.630	552	64.85	64.85	Miami	852	207	292	377	462
					New Orleans	58	196	282	367	452
					Houston	403	199	283	368	453
Brownsville					Houston	357	197	282	367	452
Puerto Rico	0.765	688	80.80	80.80	New York	1609	196	281	367	452
					Miami	1104	188	273	358	444
					New Orleans	1772	197	282	367	452
					Houston	1972	197	282	374	453
Hawaii	0.812	711	83.58	83.58	Los Angeles	2953	198	283	363	453
Brazil	0.791	695	81.63	[illegible]	New York	[illegible]	228	313	398	483
					Miami	[illegible]	227	312	397	482
					New Orleans	4829	238	323	409	494
					Houston	4966	239	324	409	494

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Table 12. OTEC PRODUCED PROCESS HEAT VIA MOLTEN SALTS BRIDGE DELIVERED TO VARIOUS SITES ($\$/10^6$ Btu, 1976 Dollars)

OTEC Site	Net Capacity Factor	Annual Electricity Production, 10^6 $kWhr_e$	Annual Molten Salts Production, 10^6 $kWhr_t$	Annual Molten Salts Delivery, 10^6 $kWhr_t$	Destination	Distance, Statute Miles	Delivered Cost of Molten Salts: 10 Mills ($\$/10^6$ Btu)	20 Mills	30 Mills	40 Mills
Key West	0.750	657	519.95	519.95	New York	1377	45.80	49.51	53.21	56.91
					Miami	250	14.62	18.32	22 02	25.73
					New Orleans	603	25.65	29.35	33.05	36.76
					Houston	803	30.01	33.71	37.42	41.12
West Florida	0.720	631	499.15	499.15	Miami	516	23.07	26.79	30.48	34.18
					New Orleans	345	19.40	23.10	26.80	30.51
					Houston	610	26.83	30.53	34.23	37.94
Miami	0.792	694	549.07	549.07	New York	1145	39.38	43.10	46.78	50.48
					Miami	10	4.66	8.37	12.06	16.03
					New Orleans	852	30.13	33.84	37.54	41.24
					Houston	1052	36.28	39.98	46.68	47.38
New Orleans	0.640	552	436.76	436.76	Miami	852	36.93	40.63	44.33	48.04
					New Orleans	58	8.22	11.93	15.63	19.33
					Houston	403	24.66	28.36	32.06	35.77
Brownsville	0.635	557	440.22	440.22	Houston	357	22.12	25.83	29.53	33.23
Puerto Rico	0.785	688	544.21	544.21	New York	1609	48.47	52.17	55.88	59.58
					Miami	1104	38.26	41.96	45.66	49.36
					New Orleans	1772	51.24	54.94	58.65	62.35
					Houston	1972	56.61	60.31	64.01	67.72
Hawaii	0.812	711	562.93	562.93	Los Angeles	2953	75.19	78.89	82.59	26.29
Brazil	0.793	695	549.76	549.76	New York	4253	104.00	107.60	111.31	115.00
					Miami	3974	98.00	101.20	104.91	108.62
					New Orleans	4829	117.00	120.46	124.16	127.87
					Houston	4966	119.00	122.80	126.52	130.22

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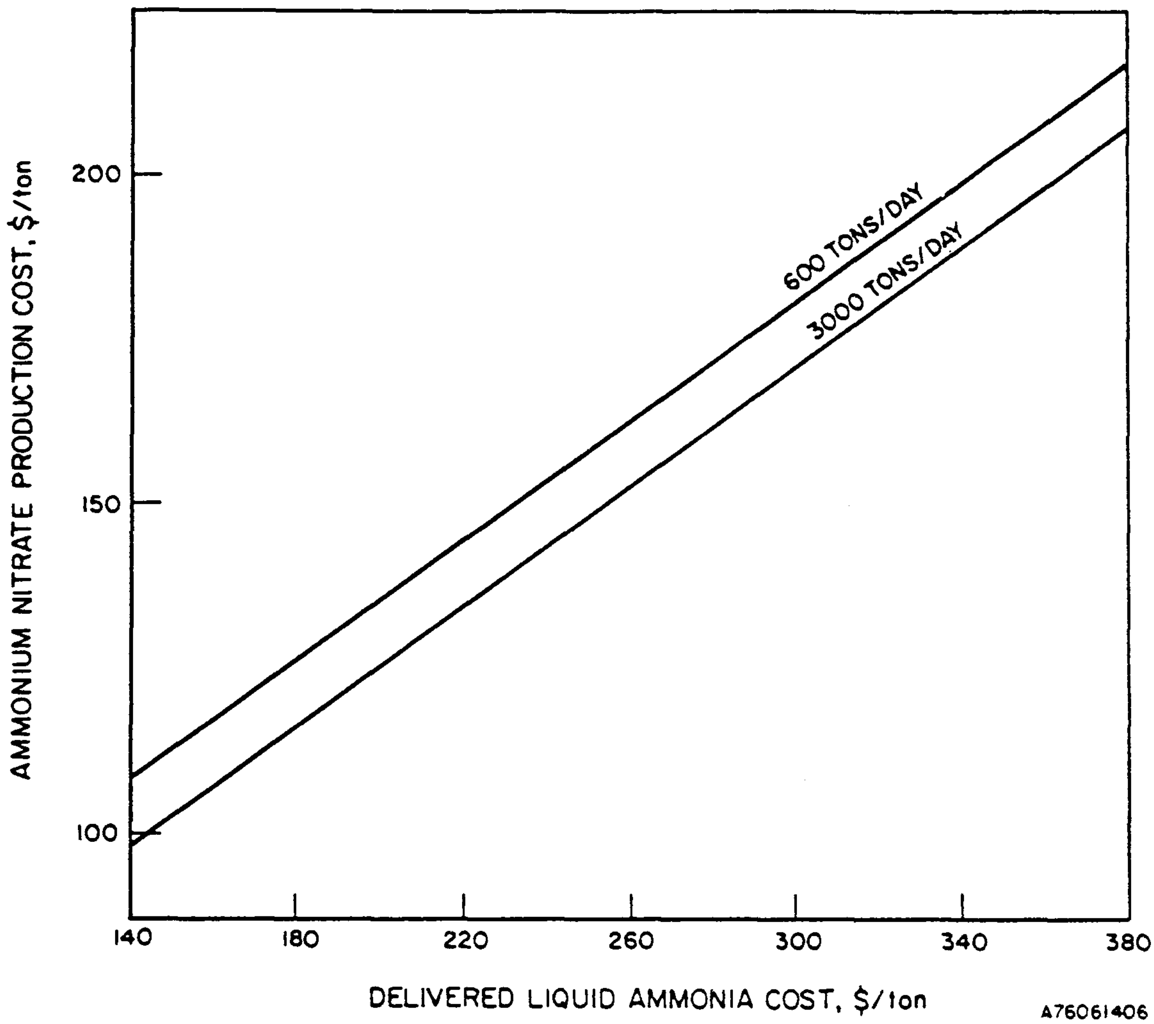

Figure 2. AMMONIUM NITRATE PRODUCTION COST VERSUS LIQUID AMMONIA DELIVERED COST

Table 13. ELECTRICITY GENERATING COSTS FOR OTEC ENERGY CARRIERS (1976 Dollars)

Energy Carrier	Annual Cost, $ X 10^6
Hydrogen (Gas)	1.75
Hydrogen (Liquid)	2.20
Ammonia	3.47
Molten Salts	1.71

Table 14. OTEC ELECTRIC POWER* DELIVERED TO DESTINATION BUSBAR VIA LIQUID HYDROGEN BRIDGE (Cost/kWhr, 1976 Dollars)

OTEC Site	Net Capacity Factor	Annual Electricity Production, 10^6 kWhr	Annual Liquid Hydrogen Production, 10^3 tons	Annual Electricity Delivery, 10^6 kWhr	Destination	Distance, Statute Miles	Delivered Electricity Cost, Conservative Assumptions: 10 Mills	20 Mills	30 Mills	40 Mills	Delivered Electricity Cost, Optimistic Assumptions: 10 Mills	20 Mills	30 Mills	40 Mills
							mills/kWhr				mills/kWhr			
Key West	0.750	657	12.31	18.994	New York	1377	175	210	244	279	157	191	256	260
			15.60†	223.48	Miami†	250	101	131	160	190	101	131	160	190
			12.31	189.94	New Orleans	603	149	183	218	253	134	168	203	238
			12.31	189.94	Houston	803	174	208	243	275	155	189	224	258
West Florida	0.720	631	11.82	182.35	Miami	516	148	182	217	252	135	170	205	239
			14.97†	214.54	New Orleans†	345	122	152	181	211	122	152	181	211
			11.82	182.35	Houston	610	154	189	223	258	138	173	207	242
Miami	0.792	694	13.00	200.58	New York	1145	168	203	237	272	149	184	219	253
			16.47†	235.99	Miami†	10	53	83	112	142	53	83	112	142
			13.00	200.58	New Orleans	852	167	201	236	270	148	183	217	252
			13.00	200.58	Houston	1052	168	202	237	271	149	184	218	253
New Orleans	0.630	552	10.34	159.55	Miami	852	201	235	270	304	177	212	246	281
			13.10†	187.72	New Orleans	58	66	96	125	154	66	96	125	154
			10.34	159.55	Houston	403	150	190	225	259	142	177	211	246
Brownsville	0.635	556	13.21†	189.21	Houston†	357	135	164	194	223	135	164	194	223
Puerto Rico	0.785	688	12.89	198.81	New York	1609	169	204	239	273	150	185	220	254
			12.89	198.81	Miami	1104	168	202	238	272	150	184	219	263
			12.89	198.81	New Orleans	1772	170	204	239	274	151	185	220	255
			12.89	194.66	Houston	1972	174	209	245	280	155	190	225	261
Hawaii	0.812	711	13.33	196.21	Los Angeles	2953	210	246	283	319	181	218	254	290
Brazil	0.793	695	13.02	183.14	New York	4253	277	315	353	391	231	269	307	345
			13.02	186.01	Miami	3974	253	290	328	365	213	250	287	325
			13.02	180.27	New Orleans	4829	298	336	375	413	246	284	323	361
			13.02	180.27	Houston	4966	298	337	375	414	246	285	323	362

* 100-MW plant using busbar costs of 10, 20, 30, and 40 mills/kWhr. Electricity costs are for baseload.

† Gaseous hydrogen.

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Table 15. OTEC ELECTRIC POWER* DELIVERED TO DESTINATION BUSBAR VIA LIQUID AMMONIA BRIDGE
(Cost/kWhr, 1976 Dollars)

OTEC Site	Net Capacity Factor	Annual Electricity Production, 10^6 kWhr	Annual Liquid Ammonia Production, 10^3 tons	Annual Electricity Delivery, 10^6 kWhr	Destination	Distance, Statute Miles	Delivered Electricity Cost, Conservative Assumptions† (mills/kWhr): 10 Mills	20 Mills	30 Mills	40 Mills
Key West	0.750	657	77.20	147.76	New York	1377	127	172	216	261
					Miami	250	117	162	206	251
					New Orleans	603	120	164	209	253
					Houston	803	121	166	210	255
West Florida	0.720	631	74.11	141.85	Miami	516	122	166	211	255
					New Orleans	345	120	165	209	254
					Houston	610	123	168	212	257
Miami	0.792	694	81.52	156.03	New York	1145	121	165	210	254
					Miami	10	113	157	202	246
					New Orleans	852	117	162	206	251
					Houston	1052	120	164	208	253
New Orleans	0.630	552	64.85	124.12	Miami	852	136	180	225	269
					New Orleans	58	131	175	220	264
					Houston	403	131	176	220	265
Brownsville	0.635	557	65.36	125.10	Houston	357	131	175	220	264
Puerto Rico	0.785	688	80.80	154.66	New York	1609	125	169	214	258
					Miami	1104	121	165	210	254
					New Orleans	1772	125	170	214	259
					Houston	1972	128	170	214	259
Hawaii	0.812	711	83.58	159.97	Los Angeles	2953	125	169	214	258
Brazil	0.793	695	81.63	156.23	New York	4253	141	186	230	275
					Miami	3974	141	185	230	274
					New Orleans	4829	147	191	236	280
					Houston	4966	147	191	236	280

* 100 MW plant using busbar costs of 10, 20, 30, and 40 mills/kWhr. Electricity costs are for baseload.

† Optimistic assumptions were not made for molten salts.

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Table 16. OTEC ELECTRIC POWER* DELIVERED TO DESTINATION BUSBAR VIA MOLTEN SALTS BRIDGE
(Cost/kWhr, 1976 Dollars)

OTEC Site	Net Capacity Factor	Annual Electricity Production, 10^6 $kWhr_e$	Annual Molten Salts Production, 10^6 $kWhr_t$	Annual Electricity Delivery, 10^6 kWhr	Destination	Distance, Statute Miles	Delivered Electricity Cost, Conservative Assumptions† 10 Mills	20 Mills	30 Mills	40 Mills
							mills/kWhr			
Key West	0.750	657	519.95	181.98	New York	1377	456	492	528	564
					Miami	250	152	188	224	260
					New Orleans	603	260	296	332	368
					Houston	803	302	338	374	410
West Florida	0.[illegible]0	631	499.15	174.70	Miami	516	235	271	307	343
					New Orleans	345	199	235	271	307
					Houston	610	271	307	344	380
Miami	0.792	694	549.07	192.17	New York	1145	393	429	465	581
					Miami	10	54	90	126	163
					New Orleans	852	303	339	375	411
					Houston	1052	363	399	435	471
New Orleans	0.630	552	436.76	152.87	Miami	852	371	407	444	480
					New Orleans	58	91	127	164	200
					Houston	403	252	288	324	360
Brownsville	0.635	557	440.22	154.08	Houston	357	227	263	299	335
Puerto Rico	0.785	688	544.21	190.47	New York	1609	482	518	554	590
					Miami	1104	382	418	454	490
					New Orleans	1772	509	545	581	617
					Houston	1972	561	597	633	669
Hawaii	0.812	711	562.93	197.03	Los Angeles	2953	742	778	814	850
Brazil	0.793	695	549.76	192.42	New York	4253	1022	1058	1094	1130
					Miami	3974	960	996	1032	1068
					New Orleans	4829	1147	1184	1220	1256
					Houston	4966	1170	1206	1243	1279

* 100 MW plant using busbar costs of 10, 20, 30, and 40 mills/kWhr. Electricity costs are for baseload.

† No optimistic assumptions were made for ammonia.

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3. TASK RESULTS

3.1 Market Potential for Ammonia

Ammonia is a critical compound for a number of industries. It is used in agriculture, refining, explosives, refrigeration, and organic and inorganic chemicals. The 1976 U.S. production of ammonia was 16.5 million short tons.[5] Assuming a 2%/year growth rate, this production is expected to increase to 20 million tons by 1985 and 27 million tons by 2000. The principal market for ammonia is in agriculture, where it is applied directly as a fertilizer or incorporated into other fertilizers such as urea, ammonium nitrate, diammonium phosphate, or ammonium sulfate. In 1976, approximately 90% of U.S. ammonia was manufactured into fertilizer and fertilizer feedstocks. The agricultural uses of ammonia so dominate the market that adverse weather or shifts in acreage planting of certain crops can have a significant effect on the market price.

The production of ammonia is a relatively simple, two-step process. The first step consists of the production of hydrogen either electrolytically or by using hydrocarbon feedstocks such as natural gas, coal, naphtha, or heavy oil. The second step is the synthesis of the hydrogen with nitrogen (usually separated from the air) to form ammonia. The process of reforming natural gas into hydrogen and the subsequent synthesis to ammonia is sufficiently straightforward that the large farm cooperatives currently dominate the production of ammonia for agriculture and are presently lobbying to keep natural gas both available and at low prices.

The demand for ammonia relative to total capacity has fluctuated over the recent past. This has been primarily caused by the over-building of production capacity as each company or cooperative makes their expansion decisions based upon identical market indicators. When the industry enters a period of overcapacity, these producers, unwilling to give up market share, often end up selling at prices close to their variable costs. The result has been wide fluctuations in spot prices for ammonia. In January 1971, the list price of ammonia was approximately $60/ton. By early 1975, it had risen to $210/ton. In October 1977, the price was down to $140/ton.[6] Because of these fluctuations, farmers are unwilling to enter into long-term contracts at prices in the middle- to high-price range, and producers are unwilling to enter into long-term contracts in the middle- to low-price range. The result is that little price stability can be built into the market. Because of these price swings, the market would be more difficult for OTEC ammonia producers than for conventional producers. The cost of OTEC ammonia would be almost totally based upon fixed costs. On the other hand, the cost of conventionally produced ammonia has variable costs (feedstocks and utilities) as a substantial proportion of total costs (in most cases, over 40%).[7] Thus, during periods of low prices, OTEC ammonia producers would lose substantially more money than conventional producers with similar total cost economics. The result is that OTEC ammonia plants will be considered very risky and will have to show a substantial cost advantage to be an attractive investment. This risk level would also preclude utility ownership of the OTEC plants. Because of this high financial risk, the potential agriculture market available for OTEC ammonia would be no more than 25% of the total agricultural market when total cost economics are compared. This would reduce the agriculture market potential for OTEC ammonia to about 5 to 7 million tons per year by the year 2000.

Because of the small size of the non-agricultural sector of the market, the other uses of ammonia probably do not offer much more attractive markets for ammonia. However, the economics of these other uses would make most of them compatible with the structure of the OTEC ammonia economics. When a facility is designed and built incorporating one or more feedstocks, a number of critical economic decisions are made based upon projected prices of those feedstocks. As a result, long-term contracts at fixed prices are more attractive than in the agriculture industry, even if the contracts are at a slightly premium price. The explosives, inorganic-chemicals, and refrigeration industries would probably be interested. The refining and organic-chemicals industries make most of their own ammonia from hydrogen-rich off-gases. Unfortunately, the potential market for OTEC ammonia for all these non-agricultural customers would be less than 2 million tons per year through 2000. Thus, the total market available for penetration for OTEC ammonia in the United States would be about 7 to 9 million tons by the year 2000.

3.2 Ammonia as a Fertilizer and Hydrogen as an Aircraft Fuel -- Competitive (Coal, LNG, Biomass) Costs and Market Penetration

3.2.1 Ammonia as Fertilizer

The results of the previous section described many of the important aspects of the fertilizer market potential for OTEC ammonia. This section deals specifically with ammonia that will be used as fertilizer. The contract specifies that the competitive costs considered will be coal, OPEC natural gas (LNG), and biomass. This assumes that no domestic natural gas will be available for ammonia production. Regardless of this assumption, the direction of domestic natural gas prices and the high likelihood of incremental pricing for all gas users other than residences would indicate that, on a delivered basis, by the 1990's, the prices of domestic natural gas and OPEC natural gas (LNG)* will be identical. Table 17 gives our estimation of the delivered price (in 1976 dollars) that coal and natural gas will have in 1985 and 2000.

Table 17. ESTIMATED DELIVERED COAL AND NATURAL GAS COSTS (1976 Dollars)

	1985	2000	Destination
Coal (Lignite), $/ton	$15.00 - $20.00	$35.00 - $40.00	Mississippi Valley
OPEC Natural Gas, $/million Btu	$4.50 - $ 5.00	$ 6.00 - $ 6.50	Texas Gulf
Conventional Natural Gas, $/million Btu	$3.00 - $ 3.50	$ 6.00 - $ 6.50	Texas Gulf

The economics of ammonia production using gas and coal have been investigated in detail.[19, 20, 21] The production of ammonia from biomass is in its infancy as a technology; as a result, we found no estimates reliable enough for this study.

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* The potential competition of ammonia produced in OPEC countries was also considered. However, the predicted natural gas prices in the various OPEC countries are so riddled with political and economic uncertainties that we considered them insufficiently accurate to be used. Needless to say, ammonia produced with feedstock costs at or below $0.25/million Btu can be significant competition despite the long transportation costs.

Given the feedstock costs in Table 17, the cost of ammonia from these sources can be readily estimated. Table 18 shows these estimates.

Table 18. ESTIMATED AMMONIA PRODUCTION COSTS: CONVENTIONAL FEEDSTOCKS (1976 Dollars)

Feedstock	Production Costs, $/ton 1985	Production Costs, $/ton 2000
Coal (Lignite)	$150 - $225	$200 - $270
OPEC Natural Gas	$220 - $260	$260 - $330
Conventional Natural Gas	$160 - $210	$260 - $330

Note: These variations are the result of the age of the equipment and in the case of coal, the coal gasification process used.

A comparison of the cost of ammonia from various sources with feedstock cost is presented in Figure 3. From Table 11, the cost of OTEC ammonia ranges between $170/ton and $500/ton, depending upon the distance the ammonia has to be shipped and the bus-bar cost of OTEC electricity. Clearly, if the cost of OTEC electricity can be kept in the 10 to 20 mills/kWhr range, the OTEC ammonia will be cost competitive by the year 2000 or before. If the OTEC electricity cost is between 5 and 10 mills/kWhr, OTEC ammonia will be cost competitive by the year 1985. This is particularly true for new ammonia capacity and when competing against OPEC natural gas. If the net bus-bar cost of OTEC electricity is over 20 mills/kWhr on the platform, OTEC ammonia will not be economically viable.

Because of the uncertainty in the cost projections for both OTEC and conventional ammonia, it is impossible to estimate market penetration precisely. Given the 4 to 5 million ton and 5 to 7 million ton potential markets for 1985 and 2000, respectively, OTEC could take as much as 0.8 million tons in 1985 and 3.5 million tons in 2000, if the OTEC bus-bar costs were kept under 10 mills/kWhr. At 20 mills/kWhr, virtually no penetration would be possible in 1985 and only 1.2 million tons by 2000. The exact level of penetration would be a function of the transport distances from the OTEC site. From the OTEC economics described in Table 11, the OTEC plants must be within 3000 miles of the destination to be competitive in 1985, if OTEC bus-bar costs are below 10 mills/kWhr. Also, to be competitive in 2000, with OTEC costs of 20 mills/kWhr, the site-to-destination distances must be less than 1200 miles.

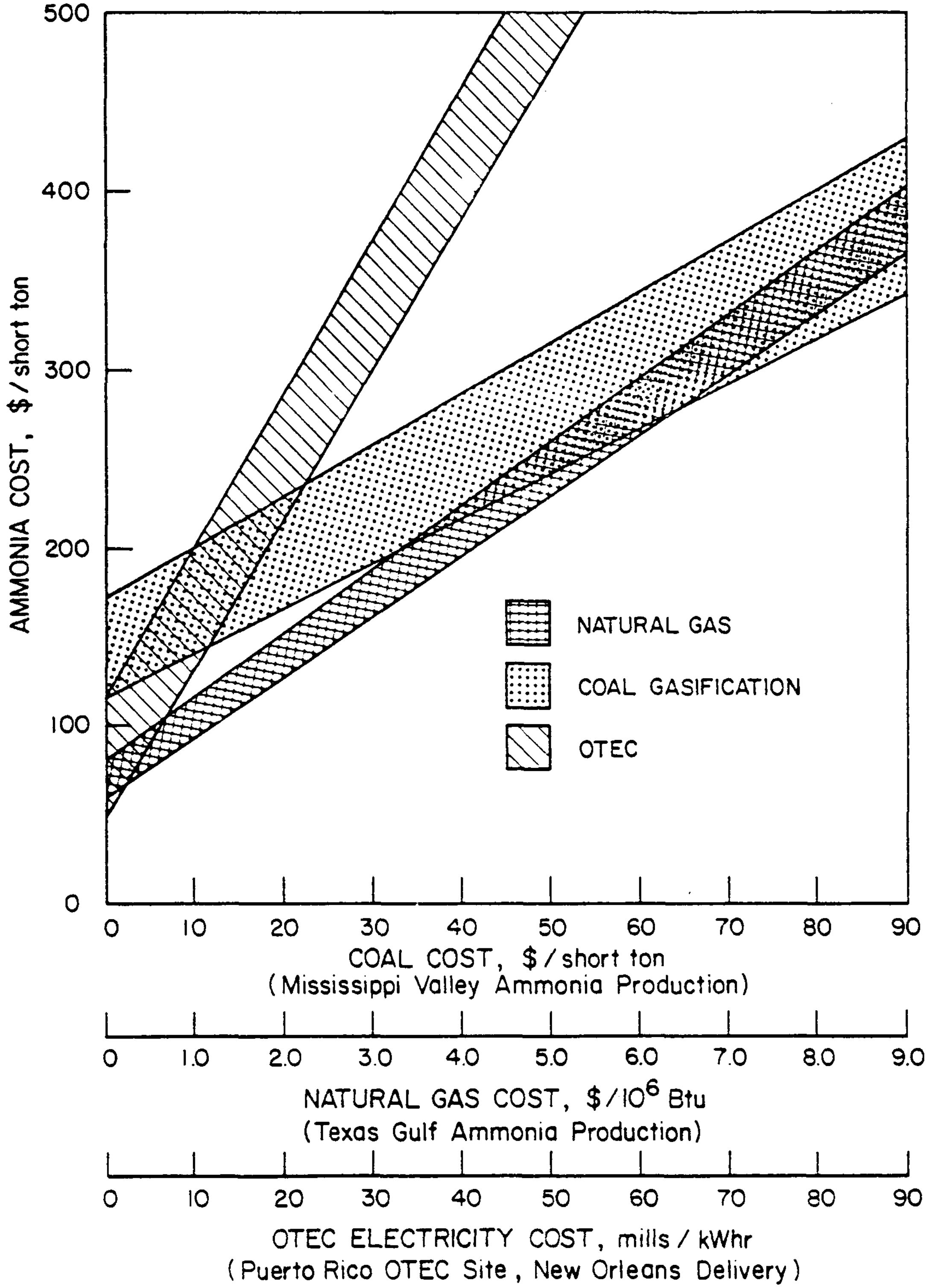

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Figure 3. AMMONIA COST AS A FUNCTION OF FEEDSTOCK COST
($/Short Ton, 1976 Dollars)

3.2.2 Hydrogen Market for Aircraft

This market does not currently exist outside of specialty needs for spacecraft. For it to come into being will depend upon the rate at which hydrogen-fueled aircraft can be designed, developed, and proven. The market will consist primarily of the fuel requirements for commercial aircraft. Initial studies have assumed that the first tests of hydrogen-fueled aircraft would be done on the San Francisco-Chicago route after 1990.[8,12] Further, service between 10 major U.S. cities and 4 foreign cities would not be implemented until the year 2000. Unfortunately, this will require a high priority national commitment to use hydrogen in the year 1980.[8] We believe that it is unlikely that such a commitment will be made until the mid-1980's, setting back schedules by at least 5 years.

The competitive sources for hydrogen for this market are coal, LNG, biomass, and off-peak electricity. A previous study[9] by IGT indicated that off-peak electricity (assuming a 20 mills/kWhr bus-bar cost) would produce hydrogen at approximately $13.50/million Btu. Our update of another IGT study[10] showed that, with $0.65/million Btu coal and using the IGT Ash Agglomerator Process, hydrogen could be obtained from coal at $3 to $4/million Btu. For steam reforming of LNG, assuming a $3.50 to $4.00/million Btu cost of gasified LNG, the cost of hydrogen would be $5.50 to $6.25/million Btu.[9] The production of hydrogen from biomass has not been investigated in sufficient detail to develop reliable cost figures. The delivered costs of OTEC and conventional hydrogen are compared in Table 19. From this table, it appears that OTEC hydrogen will not be competitive with other sources of hydrogen if it is delivered to the port as a liquid and has to be gasified prior to entering the system. The cost of hydrogen liquefaction at 20 mills/kWhr runs between $2.75 and $3.00/million Btu of hydrogen.[11] Thus, if the hydrogen from coal, LNG, or off-peak electricity must be liquefied, as it does for aircraft fuel, $2.75 to $3.00/million Btu should be added to it to compare it with the OTEC-produced liquid hydrogen. Unfortunately, even this addition does not make the most optimistic OTEC liquid hydrogen competitive with hydrogen from coal at any point. As a result, it is doubtful that OTEC liquid hydrogen will be a successful source of hydrogen for aircraft fuel in the future unless severe supply problems from those other sources develop.

Table 19. HYDROGEN COST COMPARISONS
(1976 Dollars)

Process	Hydrogen Cost, \$/million Btu 1985	Hydrogen Cost, \$/million Btu 2000	Comments
OPEC Natural Gas Reforming	7.10 - 7.80	9.25 - 10.00	\$4.50 - \$5.00 LNG in 1985;
Liquefaction Cost	2.75 - 3.00	2.75 - 3.00	\$6.00 - \$6.50 in 1990
Total	9.85 -10.80	12.00 - 13.00	(\$/10^6 Btu)
Ash Agglomerator Process	3.40 - 3.80	5.10 - 5.55	\$15.00 - \$20.00 lignite
Liquefaction Cost	2.75 - 3.00	2.75 - 3.00	
Total	6.15 - 6.80	7.85 - 8.55	
OTEC Gas (10 mills/kWhr)	5.40 -10.00	5.40 - 10.00	Distances under 200 miles
Liquefaction Cost	2.75 - 3.00	2.75 - 3.00	
Total	8.15 -13.00	8.15 - 13.00	
OTEC Liquid (10 mills/kWhr)	16.00 - 24.00	16.00 - 24.00	Distances over 200 and under 1200 miles

In those special short-distance cases where OTEC hydrogen is piped to shore as a gas, OTEC hydrogen may be viable. Reviewing the estimated OTEC hydrogen costs in Table 10 with the resulting costs of hydrogen from coal and OPEC natural gas (LNG) in Table 19, there are only two site-destination combinations where the OTEC hydrogen could be even marginally competitive by the year 2000. (None are competitive in 1985.) These are Miami-Miami and New Orleans-New Orleans. Therefore, the key is that the hydrogen does not have to be transported more than 100 miles, and based upon the short-distance requirement, the OTEC hydrogen would only be competitive in the New Orleans and Miami markets. However, New Orleans is not expected to be in the original group of cities expected to have hydrogen service for aircraft by the year 2000.[8,12] Previous studies estimated that San Francisco will require 293 million pounds per year[8] of liquid hydrogen and Chicago, 584 million pounds per year.[12] Assuming that the Miami fuel requirement was half-way between New Orleans and Chicago, this would yield a hydrogen fuel requirement of 440 million pounds per year. At a maximum, OTEC platforms in the Miami area could supply 440 million pounds per year of hydrogen to Miami for aircraft fuel. Other sources would probably be required to minimize the dependence of the airport on one source. So from a practical standpoint, the market penetration could probably be no more than 50% of the Miami requirement. Thus, the market for OTEC hydrogen for aircraft fuel in the year 2000 would be about 220 million pounds per year (13 trillion Btu).

3.3 OTEC Hydrogen, Liquid Ammonia, and Molten Salt Carriers for the Production of Peaking Electricity

DOE has estimated the total additions to U.S. electrical capacity to be between 725 and 1830 GW_e for the period 1975 to 2000. Of that, 250 to 750 GW_e (33% to 40%) will go to peaking. General Electric has estimated that during the period 1990 to 2020, the peaking capacity additions will be between 198 and 460 GW_e.[2]

Within the United States, there are five regions which could potentially benefit from OTEC electricity due to their proximity to OTEC sites. These have been identified according to the National Electric Reliability Council breakdown, and are presented below.

ERCOT - Electric Reliability Council of Texas

MAAC - Mid America Area Council

SERC - Southeastern Electric Reliability Council

SPP - Southwest Power Pool

WSCC - Western Systems Coordinating Council.

Table 20 shows the DOE estimate of the total generating capacity for each region in the years 1975, 2000, and 2020.

Table 20. ESTIMATED REGIONAL GENERATING CAPACITY[13] FOR 1975, 2000, AND 2020

Region	1975	2000 Low Demand	2000 High Demand	2020 Low Demand	2020 High Demand
	GW_e				
ERCOT	32	75	170	120	310
MAAC	42	65	110	100	220
SERC	110	255	590	460	1200
SPP	40	90	210	215	580
WSCC	89	155	305	255	600
Total	313	640	1385	1150	2910

Growth Rate, High Demand	1975-2000	6.1% Compounded Annually
	2000-2020	3.8% Compounded Annually
Growth Rate, Low Demand	1975-2000	2.9% Compounded Annually
	2000-2020	2.9% Compounded Annually

Table 21 shows the DOE cost estimates for baseload (not including intermediate or cycling capacity) electric power during the 1975 to 2020 period.

Table 21. ESTIMATED REGIONAL ELECTRIC POWER COSTS:[13] CONVENTIONAL TECHNOLOGY BASELOAD GENERATION, BUS-BAR COST (1976 Dollars)

Region	Coal 1990	Coal 2000	Coal 2020	Nuclear 1990	Nuclear 2000	Nuclear 2020
	mills/kWhr					
ERCOT	20	21	22	15	19	22
MAAC	22	24	27	16	20	21
SERC	21	24	25	15	19	21
SPP	20	21	23	17	20	22
WSCC	17	19	21	16	19	21

In 1975, the U.S. peaking capacity was approximately 20% of the total demand for electricity. Using the 33% (low demand) to 40% (high demand) DOE estimates of peaking capacity to total capacity additions, the market for new peaking capacity in the five regions would be as shown in Table 22.

Table 22. ESTIMATED NEW PEAKING ADDITIONS
(1975 to 2000, and 2000 to 2020)

	Low Demand		High Demand	
	1975 - 2000	2000 - 2020	1975 - 2000	2000 - 2020
Region	GW_e			
ERCOT	14	15	55	56
MAAC	8	12	27	44
SERC	48	68	192	244
SPP	17	42	68	148
WSCC	22	33	86	118
Total	109	170	428	610

We were not able to identify estimates of peaking costs or capacity on a region-by-region basis. At 1976 prices, the capital, operating, and maintenance costs of conventional gas turbine peaking equipment are about 13 mills/kWhr. Fuel for the turbines is needed at a rate of about 11,000 Btu/kWhr. Peaking costs as a function of fuel costs are shown in Figure 4. On a nationwide basis, the cost of peaking electricity using conventional gas turbine technology was about 40 to 50 mills/kWhr in 1975. By 2000, the cost of peaking electricity is estimated to rise to 60 to 70 mills/kWhr, and by 2020, to 85 to 95 mills/kWhr. The cost of peaking electricity will probably be on the upper end for the MAAC and SERC regions unless substantial gas deposits are found off the Atlantic coast, and are allowed to be used for this purpose.

Comparing the predicted costs of baseload electricity using OTEC-produced hydrogen, ammonia, and molten-salt carriers in Tables 14, 15, and 16, respectively, with the predicted costs of peaking electricity using conventional gas turbines and other predicted peaking technologies, the level of market penetration will be severely limited.

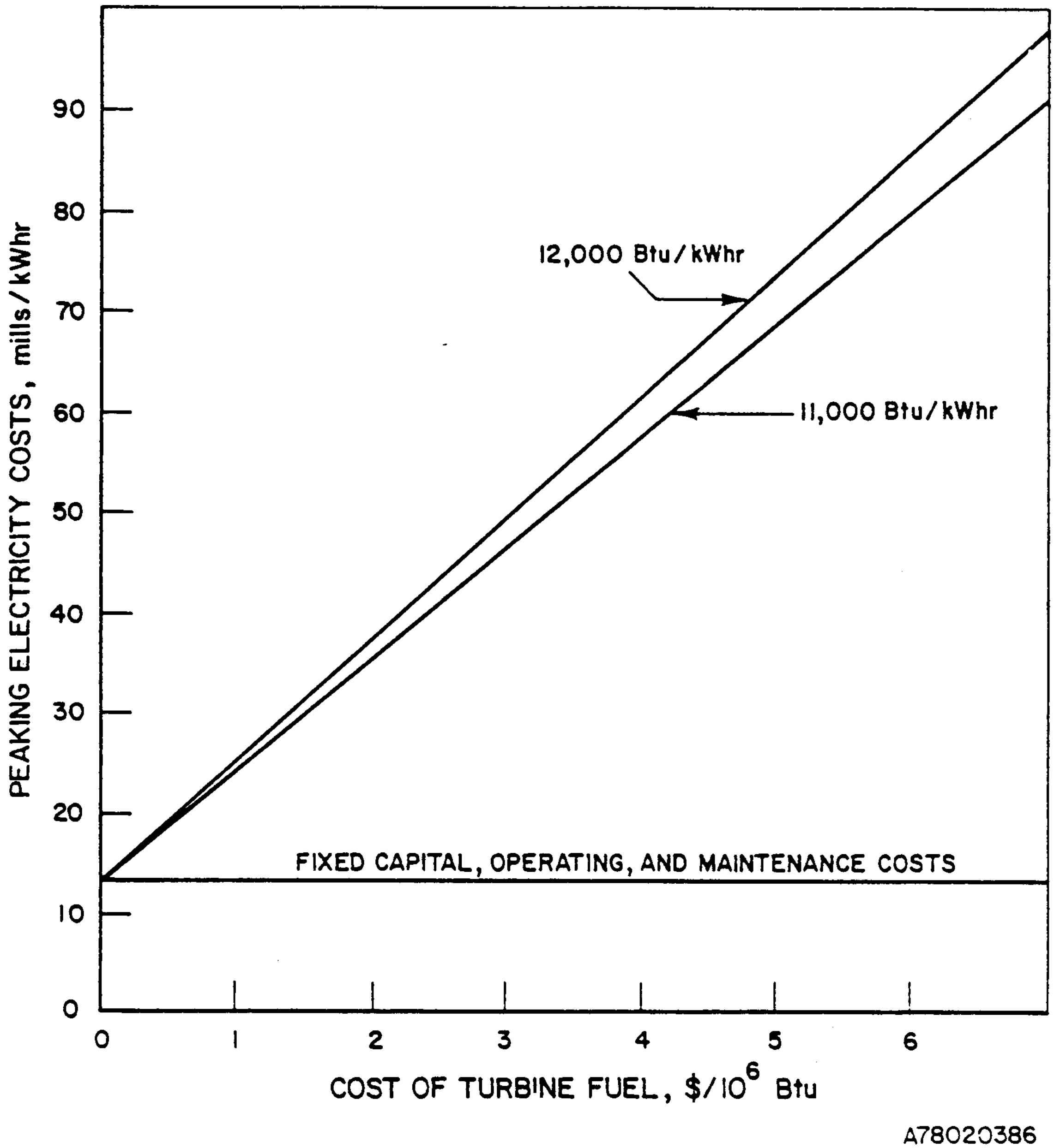

Figure 4. U.S. PEAKING COSTS:
CONVENTIONAL GAS TURBINE TECHNOLOGY

Calculations of the costs of using these OTEC carriers in a peaking mode proved unnecessary as the baseload costs are higher than those for current and predicted competing peaking technologies.

If the economic predictions of some of the new technologies for peaking become a reality, the chances of using hydrogen, ammonia, or molten-salt carriers to help OTEC-source electricity be competitive are negligible. One such technology, incorporating a thermal storage media, is predicted to have 26 mills/kWhr peaking electricity.[13] Because this is essentially the same technology used for molten salts, there is little chance that the economics of the OTEC molten salts would become a reality and those for the land-based thermal media would not. These competitive technologies will make the peaking market extremely difficult for electricity from hydrogen or molten salts. As a result, we predict that these carriers will have virtually no penetration into the electric utility peaking markets.

3.4 Ammonium Nitrate Fertilizer Market Penetration

The total demand for ammonium nitrate in 1976 was 7.2 short tons;[5] of this amount, 6% was used for fertilizers, 74% for fertilizer feedstocks, and the remaining 20% for explosives and other uses.[5] If the market for fertilizer-oriented ammonium nitrate grows at 2% per year through 2000, the total market will be approximately 7 million tons in 1985 and 9.3 million tons by 2000.

Ammonium nitrate economics are totally dependent upon the cost of ammonia. The extent to which ammonium nitrate from OTEC-based ammonia will penetrate the fertilizer marketplace is totally dependent upon the relative economics of OTEC ammonia versus that from coal or conventional natural gas. Further, the ammonium nitrate demand is subject to the same fluctuations as agricultural ammonia. The production is equally controlled by the large farm cooperatives. For the same risk-related reasons as described in the previous sections, we expect the market for OTEC ammonium nitrate to be limited to only 25% of the total market. As a result, only 1.6 to 1.8 million tons and 2.2 to 2.5 million tons will be available to OTEC ammonium nitrate in 1985 and 2000, respectively. Given the ammonia economics discussed in Section 3.2, the maximum market penetration for OTEC ammonium nitrate will probably be only 0.3 million tons in 1985 and 1.2

million tons in 2000 if the OTEC bus-bar costs can be kept below 10 mills/kWhr. If the OTEC bus-bar costs are between 10 and 20 mills/kWhr, we expect no market penetration by 1985 and perhaps as much as 0.4 million tons by 2000. From the ammonia economics described in Table 11, the OTEC plant sites must be within 3000 miles of the destination to be competitive in 1985, with OTEC bus-bar costs below 10 mills/kWhr. Likewise, to be competitive in 2000 with OTEC bus-bar costs of 20 mills/kWhr, the site-destination distances must be less than 1200 miles.

3.5 OTEC Hydrogen for Baseload Electricity, and Industrial and Domestic Fuels — Competitive Costs and Market Penetration

3.5.1 OTEC Hydrogen for Baseload Electricity

Table 21 projects bus-bar costs in the year 2000 for baseload electricity in the 19 to 24 mills/kWhr range using conventional coal and nuclear technology. Table 14 projects the bus-bar costs for electricity using OTEC hydrogen and a gas turbine/generator combination in the 53 to 362 mills/kWhr range. The most optimistic cost — 53 mills/kWhr — is based upon 10 mills of electricity at the OTEC platform and 43 mills of electrolysis, transportation, and fuel-cell cost. To be competitive under the most optimum conditions, i.e., pipeline transportation rather than liquefaction and barge transportation, the OTEC platform would have to be able to produce electricity at a rate less than 0 mills/kWhr (an obvious impossibility). As a result, OTEC hydrogen as a source of electric baseload power is not economically practical.

3.5.2 OTEC Hydrogen for Industrial and Domestic Fuels

Table 10 shows the projected delivered costs of hydrogen on a dollars/million Btu basis. The size of the market for domestic and industrial fuels in the United States is predicted[14] to be 59 quadrillion Btu by 1985 and 89 quadrillion Btu by 2000. As a gas, limited to customers who would be served by conventional or synthetic natural gas, this market is predicted to be 15 quadrillion Btu by 1985[14] and 17 quadrillion Btu by 2000. The potential competitors for this market are conventional natural gas, OPEC natural gas (LNG), other sources of hydrogen, and synthetic natural gas (syngas) from coal.

The predicted costs of these fuels on a per Btu basis are given in Table 23.

Table 23. PREDICTED FUEL COSTS: CONVENTIONAL AND NEW TECHNOLOGIES (1976 Dollars)

Fuel	Fuel Costs 1985	Fuel Costs 2000
	$/10^6 Btu	$/10^6 Btu
Conventional Natural Gas[15]	3.00 - 3.50	6.00 - 6.50
OPEC Natural Gas (LNG)[15]	4.50 - 5.00	6.00 - 6.50
Syngas From Coal[15]		
High-Btu	3.00 - 3.75	4.50 - 5.50
Low-Btu	3.00 - 3.30	3.50 - 5.00
Hydrogen From Coal[10]	3.40 - 3.80	5.10 - 5.55
OTEC Hydrogen	5.40 - 10.40	5.40 - 10.40

Given the expected costs for syngas from coal, OTEC hydrogen has little chance of being competitive in 1985. In 2000, the lower costs of low-Btu syngas will exclude OTEC from a substantial portion (30%) of the industrial market. Remaining will be a very narrow market with severe constraints. The site-destination distance must be under 25 miles; thus, only the Miami-Miami site-destination combination is competitive. Further, the cost of OTEC electricity at the platform bus-bar has to be 10 mills/kWhr or less.

The estimated natural gas comsumption for Florida in the year 2000 is estimated to be in the range of 180 to 200 trillion Btu (essentially no growth from 1970). Because of its distance from the predicted sources of syngas, the cost of delivered syngas from coal will probably be on the high end of the $4.50 to $5.50 range, i.e., $5.20 to $5.50 per trillion Btu. Assuming that the Miami area would constitute between 15% and 25% of the state's consumption, that local market would be approximately 30 to 50 trillion Btu. Assuming that the fuel system in Florida would be flexible enough to supply Miami if the OTEC plant was shut down, the maximum market penetration would be 27 to 45 trillion Btu (90%). If Miami were to be isolated from the rest of the Florida system, an additional source of hydrogen would be necessary, and the maximum market penetration would be limited to about 75% of the market or 23 to 38 trillion Btu. This estimate is based upon the assumption that substantial one-time costs to adapt the Miami system to hydrogen are negligible. However, if major investments were needed, the chance of OTEC hydrogen being competitive with syngas would be nonexistent. If hydrogen were just to be injected into the Miami natural-gas system, the potential market would be significantly reduced. The estimated limit of hydrogen that can be injected into the conventional gas system without needing modifications is 10% by volume. This would reduce the maximum market penetration to 1.0 to 1.8 trillion Btu.

3.6 OTEC Molten Salts as a Heat Source for Process Applications — Competitive Costs and Market Penetration

The sources of process heat are extensive; they range from nuclear energy to coal. Cost predictions for 1985 and 2000 range from the $3 to $5/million Btu level for nuclear energy and some conventional fuels to the $15 to $20/million Btu level for electric resistance heating. The cost of using molten salts ranges from $4.70/million Btu under ideal conditions to over $130/million Btu. Only under the ideal conditions would there be any chance of OTEC heat using molten salts, making any market inroads in the process heat area very slim. These ideal conditions are: 10-mill OTEC electricity, the Miami — Miami site-destination combination, and the year 2000 market.

Unfortunately, several other factors will influence the situation negatively. First, Miami industry does not have a significant process heat requirement.[16] Second, because of the OTEC investment in transportation equipment, for the process heat to be economical, the industrial companies would have to require the heat 24 hours a day. Third, the users of the process heat would need a docking facility for the transportation vessel within a very short distance of the facility requiring the heat. Fourth, each OTEC platform, and thus transportation vessel, would be producing heat at a rate of about 1.8 trillion Btu/year. As a result, a number of users would have to be clustered around each docking facility. The implication is that the facility locations for the users would be dictated by the availability of inexpensive OTEC heat. For the user management, the risk in making such a location decision would be substantial. The result is that we doubt that molten salts as a carrier of OTEC heat would be able to achieve any market penetration, certainly none in 1985 and most likely none in 2000.

4. CONCLUSIONS

In this report, we have determined the market penetration potential for the different carriers in terms of the quantity of that carrier (or electricity generated) that would be sold. In Table 24, we show a consolidation of those quantities, expressed in terms of the OTEC generating capacity required.

The results of this study are, on the whole, negative toward the viability of lithium/lithium hydroxide, hydrogen, ammonia, and molten salts as economical carriers of OTEC-produced energy. Before being disillusioned, however, one must remember the parameters around which this study was based. First, the OTEC power was assumed to have a net cost between 10 and 40 mills/kWhr. Several prominent investigators of OTEC energy [17,18] have predicted that power costs in the 5 mills/kWhr range may be attainable with special government concessions and experience in the construction of OTEC platforms. Second, the platforms were assumed to have a 100-MW nominal capacity, a reasonable estimate for the period when OTEC systems are being introduced. As experience is gained, 500 or even 1000-MW units will be built. This increased sizing will affect OTEC, carrier production, and transportation economics, allowing for more economical vessel and pipeline utilization. A very rough estimate by IGT has indicated that clusters of ammonia OTEC platforms having a total nominal capacity of 1500 MW or more could reduce transportation costs by as much as 25% in some cases. This sensitivity is so large that a more detailed study in recommended. Third, seasonal variation capacity factors were introduced into the calculations. In the case of the New Orleans OTEC site, the annual output of electricity was only 63% of the nominal capacity. If this seasonal variation capacity factor is too pessimistic, obviously the overall economics would improve proportionately. As the understanding of OTEC and potential energy carriers progresses and some of these constraints are modified, the results of these predictions will no doubt be changed and the economics will probably improve.

Table 24. POTENTIAL MARKET PENETRATION FOR OTEC ENERGY IN TERMS OF INSTALLED OTEC CAPACITY (Nominal; in Gigawatts)

Market	Carrier	OTEC Busbar Costs Mills/kWhr	Installed OTEC Capacity 1990 (GW)	Installed OTEC Capacity 2000 (GW)
I. Electrical Generation				
Baseload	Lithium	< 11	0	0
		11-20	0	0
		21-30	0	0
		31-40	0	0
	Hydrogen	< 11	0	0
		11-20	0	0
		21-30	0	0
		31-40	0	0
Peaking	Lithium†	< 11	0	0
		11-20	0	0
		21-30	0	0
		31-40	0	0
	Hydrogen	< 11	0	0
		11-20	0	0
		21-30	0	0
		31-40	0	0
	Ammonia	< 11	0	0
		11-20	0	0
		21-30	0	0
		31-40	0	0
	Molten Salts	< 11	0	0
		11-20	0	0
		21-30	0	0
		31-40	0	0
II. Fertilizers				
Ammonia and Fertilizers Feedstocks	Ammonia	< 11	1.5	4.7
		11-20	0	2.2
		21-30	0	0
		31-40	0	0
Ammonium Nitrate*	Ammonia	< 11	0.2*	0.7*
		11-20	0	0.2
		21-30	0	0
		31-40	0	0
III. Hydrogen Aircraft Fuel	Hydrogen	< 11	0	0.7
		11-20	0	0
		21-30	0	0
		31-40	0	0
IV. Industrial and Domestic Fuel	Hydrogen	< 11	0	0.2
		11-20	0	0
		21-30	0	0
		31-40	0	0
V. Process Heat	Molten Salts	< 11	0	0
		11-20	0	0
		21-30	0	0
		31-40	0	0
Total		< 11	1.5	5.6
		11-20	0	2.2
		21-30	0	0
		31-40	0	0

* The ammonia requirement for ammonia nitrate is included in the ammonia and fertilizer feedstocks figures.

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† Based on high-demand, conservative cost case.

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APPENDIX A. REVISED FINAL LETTER REPORT ON GE/TEMPO SUBCONTRACT 29343 (IGT Project 9518)

IGT

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December 22, 1977

General Electric — TEMPO
777 14th Street, N.W.
Washington, D.C. 20005

Attention: Mr. E. Tschupp

Re: Final Letter Report on GE-TEMPO Subcontract 29343 (IGT Project 9518) Revised January 1979

Gentlemen:

This letter is IGT's final report under GE-TEMPO subcontract 29343. The tasks to be performed by IGT on a level of effort basis were:

A. Identification of the Market Potential of High Priority Missions

For OTEC energy busbar cost of 10, 20, 30, and 40 mills per kWhr, IGT shall determine the market potential for shipment of OTEC electricity via lithium hydroxide to other storage cells based on ocean sites to be selected by DOE.

B. Participate in a liaison capacity at GE-TEMPO/DOE meeting on September 30, 1977 in Washington, D.C.

A summary of the results of our work under Task 1 are contained in this letter in three sections:

1. Delivered Electricity Costs for OTEC electricity.

2. Potential market for electricity.

3. Market potential for OTEC electricity.

During the course of our work under GE-TEMPO subcontract 29412, new information may be developed which will augment the information presented here. At the time of the writing of the final report for subcontract 29412, the results here will be reviewed and modified if necessary.

At the request of Mr. Tschupp, I attended the November 9, 1977 meeting of GE-TEMPO and DOE instead of the September 30, 1977 meeting.

1. . Delivered Electricity Cost for OTEC Electricity Using a Lithium/Lithium Hydroxide Electrochemical Bridge

At the request of DOE through Mr. Tschupp the delivered electricity costs were based upon OTEC electricity produced at the following ocean locations: Hawaii, Brazil, Puerto Rico, Brownsville (Texas), New Orleans, West Florida, Key West, and Miami. Because of temperature differential variations, each production location was given a seasonal variation capacity factor correction. This correction was used with an assumed 90% operating factor to determine the net capacity factor of each OTEC location. This information is presented in the appendix to this letter report. The net capacity factors were then used to calculate the total electricity production for each site.

The OTEC plants chosen were the 100-MW design. The choice of 100-MW OTEC platforms operating as single units made a large impact of the ultimate carrier costs. By clustering OTEC plants with over 1500-MW nominal capacity in groups, tanker ships can often be used in place of ocean-going barges. Further, by using OTEC plants with unit capacities in excess of 100-MW, economics-of-scale can be realized on the costs of the basic OTEC plant and the carrier production plants. The decision to limit the study to single 100-MW plants was based upon the belief that the larger, clustered, or grazing plants would not reach commercial maturity within the 1980 to 2000 time frame of this study. Because the delivered costs are to be based on 10, 20, 30, and 40 mills/kWhr busbar costs, the specific capital and operating costs and technology level used for the platform production of OTEC electricity were of no consequence to this analysis.

The lithium/lithium hydroxide electrochemical bridge used to deliver the electricity to shore was based on advanced long range improved technology. The overall efficiency of the bridge is assumed to be 62.1% from OTEC busbar to shore busbar. The OTEC plant is assumed to produce 180.36 short tons/day of lithium metal from the 65% lithium hydroxide slurry.*

* The details of this system are presented in IGT's draft final report titled "Alternate Energy Transmission Systems From OTEC Plants" submitted September, 1977 to DOE.

The shipment of the lithium and lithium hydroxide takes place in ocean-going barge/tug combinations estimated at $150/ton of capacity. The annual fixed charge rate used for these calculations is 18.6% including capital recovery, income tax, and insurance. The inventory of lithium is estimated at $2/lb with the total inventory varying with distance.

The cost of delivered electricity has been calculated for 10, 20, 30, and 40 mills per kilowatt hour at the OTEC busbar. The results of these calculations are shown in Table 1 using optimistic and conservative assumptions* for the economics of the oxidation and reduction cells for the lithium and lithium hydroxide.

2. Potential Market for Electricity at Selected Ocean Sites

We have broken the market for electricity down into two segments, base load and peaking. DOE* has estimated the total additions to U.S. capacity to be between 725 and 1830 GW_e for the period 1975 to 2000. Of that, 250 to 750 GW_e (33% to 40%) will go to peaking. General Electric has estimated that during the period 1990 to 2020 the peaking capacity additions will be 198 and 460 GW_e.**

Within the U.S., there are five regions which could potentially benefit from OTEC electricity due to their proximity to OTEC sites. These have been identified according to the National Electric Reliability Council breakdown, and are presented below.

ERCOT - Electric Reliability Council of Texas
MAAC - Mid America Area Council
SERC - Southeastern Electric Reliability Council
SPP - Southwest Power Pool
WSCC - Western Systems Coordinating Council.

Table 2 shows the DOE* estimate of the total generating capacity for each region in the years 1975, 2000, and 2020.

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* ERDA 76-141, (Discussion Draft), Comparing New Technologies for the Electric Utilities 12/9/76, Draft Final Report (Revision-A).

** See appendix to letter report.

Table 1. OTEC ELECTRIC POWER* DELIVERED TO DESTINATION BUSBAR VIA LITHIUM/LITHIUM HYDROXIDE BRIDGE (1976 $/kWhr)

OTEC Site	Net Capacity Factor	Annual Electricity Production, 10^6 kWh	Annual Lithium Production, 10^3 tons	Annual Electricity Delivery, 10^6 kWh	Destination	Distance, St. Miles	Delivered Electricity Cost,** Conservative Assumptions (Mills/kWh): 10 Mills	20 Mills	30 Mills	40 Mills	Delivered Electricity Cost,** Optimistic Assumptions (Mills/kWh): 10 Mills	20 Mills	30 Mills	40 Mills
Key West	.750	657	49.37	408	New York	1380	80	96	112	128	67	83	99	115
					Miami	250	57	74	90	106	44	60	77	93
					New Orleans	600	64	80	96	112	51	67	83	99
					Houston	800	68	84	100	116	55	71	87	103
West Florida	.720	631	47.40	391	Miami	515	64	80	96	112	50	66	82	98
					New Orleans	345	61	77	93	109	47	55	79	95
					Houston	610	66	82	99	114	52	68	84	101
Miami	.792	694	52.14	431	New York	1145	73	89	105	121	61	77	93	109
					Miami	10	54	70	86	102	41	57	74	90
					New Orleans	850	66	82	99	115	54	70	86	102
					Houston	1050	71	87	103	119	59	75	91	107
New Orleans	.630	552	41.47	343	Miami	850	79	95	111	128	64	80	96	112
					New Orleans	60	64	80	96	112	48	65	81	97
					Houston	400	68	84	100	117	53	69	85	101
Brownsville	.635	556	41.80	345	Houston	355	67	83	99	109	51	67	83	94
Puerto Rico	.785	688	51.68	427	New York	1610	82	98	113	130	70	86	100	118
					Miami	1105	73	89	105	121	60	76	92	108
					New Orleans	1770	85	101	118	134	73	89	105	121
					Houston	1970	89	105	121	137	76	92	108	125
Hawaii	.812	711	53.46	442	Los Angeles	2955	104	120	136	152	92	108	124	140
Brazil	.793	695	52.20	431	New York	4255	129	145	161	177	117	133	149	165
					Miami	3975	127	143	159	175	114	130	147	163
					New Orleans	4810	142	158	174	190	129	145	162	178
					Houston	4965	146	162	179	195	134	150	166	182

* 100 Megawatt plant
10, 20, 30, 40 mills/kWh OTEC busbar costs.

** Base load

Table 2. ESTIMATED REGIONAL GENERATING CAPACITY* FOR 1975, 2000 AND 2020

Region	1975	2000 Low Demand	2000 High Demand	2020 Low Demand	2020 High Demand
	GW_e				
ERCOT	32	75	170	120	310
MAAC	42	65	110	100	220
SERC	110	255	590	460	1200
SPP	40	90	210	215	580
WSCC	89	155	305	255	600
Total	313	640	1385	1150	2910

Growth Rate, High Demand	1975-2000	6.1% Compounded Anually
	2000-2020	3.8% Compounded Anually
Growth Rate, Low Demand	1975-2000	2.9% Compounded Anually
	2000-2020	2.9% Compounded Anually

Table 3 shows the DOE cost estimates for base load (not including intermediate or cycling capacity) electric power during the 1975 to 2020 period.

In 1975, the U.S. peaking capacity was approximately 20% of the total. Using the 33% (low demand) to 40% (high demand) DOE estimates of peaking capacity to total capacity additions, the market for new peaking capacity in the five regions would be as shown in Table 4.

We were not able to identify estimates of peaking costs or capacity on a region-by-region basis. At 1976 prices, the capital, operating and maintenance costs of conventional gas turbine peaking equipment are about 13 mills per kilowatt hour. Fuel for the turbines is needed at a rate of about 11,000 Btu's per kilowatt hour. Peaking costs as a function of fuel costs are shown in Figure 1. On a nationwide basis, the cost of peaking electricity using conventional gas turbine technology was about 40 to 50 mills/kWhr in 1975. By 2000, the cost of peaking electricity is estimated to rise to 60 to 70 mills/kWhr and by 2020 to 85 to 95 mills/kWhr. The cost of peaking electricity will probably be on the upper end for the MAAC and SERC regions unless substantial gas deposits are found off the Atlantic coast.

Table 3. ESTIMATED REGIONAL ELECTRIC POWER COSTS*
CONVENTIONAL TECHNOLOGY BASELOAD GENERATION, BUSBAR COST
(In 1976 Dollars)

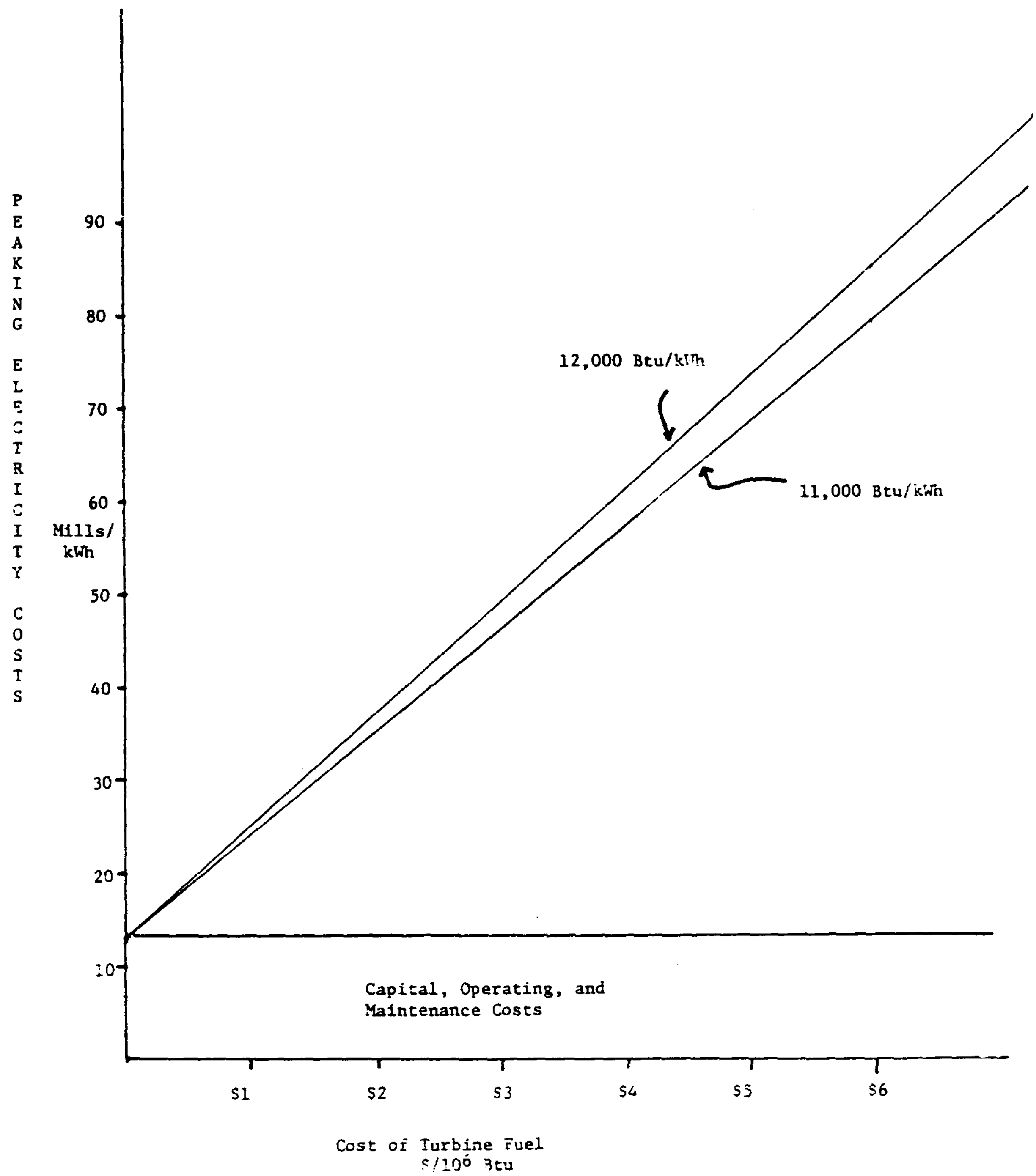
	Coal			Nuclear		
Region	1990	2000	2020	1990	2000	2020
	Mills/kWh					
ERCOT	20	21	22	15	19	22
MAAC	22	24	27	16	20	21
SERC	21	24	25	15	19	21
SPP	20	21	23	17	20	22
WSCC	17	19	21	16	19	21

* Source: ERDA, op cit.

Table 4. ESTIMATED NEW PEAKING ADDITIONS
1975 TO 2000 AND 2000 TO 2020

	Low Demand		High Demand	
Region	1975-2000	2000-2020	1975-2000	2000-2020
	GW_e			
ERCOT	14	15	55	56
MAAC	8	12	27	44
SERC	48	68	192	244
SPP	17	42	68	148
WSCC	22	33	86	118
Total	109	170	428	610

Figure 1. U.S. PEAKING COSTS
CONVENTIONAL GAS TURBINE TECHNOLOGY



3. Market Potential for OTEC Electricity Using the Electrochemical Bridge At The Selected Ocean Sites

Projected conventional base load electric power costs in each region are substantially (50%) below our estimated costs for delivered OTEC electric power. As a result, we project that there will be no market penetration for baseload electricity using the lithium/lithium hydroxide electrochemical bridge.

Projected conventional peaking load electric power costs are substantially higher than the baseload costs. As a result, there is a much greater chance that OTEC electricity can enter the peaking market. The projected busbar costs in a peaking mode of conventional electricity have been compared to the corresponding costs of lithium/lithium hydroxide battery electricity. The lithium costs are based on the baseload costs in Table 1. Using a peaking schedule of 1140 hours per year, a premium must be added to the baseload costs reflecting the part of the year when the batteries would be ready but not supplying electricity, i.e., 7620 hours per year. Table 5 shows the premiums. Against these premiums, a credit of 7 to 11 mills per kWhr can be applied to reflect a potential reduction in spinning reserve required by a utility system during the non-peak hours.

Table 5. PEAKING COST PREMIUMS

OTEC Location	Conservative Case	Optimistic Case
	mills/kWhr	
Key West	97	62
West Florida	101	64
Miami	91	58
New Orleans	115	73
Brownsville	114	73
Puerto Rico	92	59
Hawaii	89	57
Brazil	91	58

The results of the comparisons indicate that under the basic assumptions of this project, i.e., 1140 hours/year peaking, 100 megawatt (nominal) OTEC plant capacity, seasonal capacity factors, and barge transportation, the lithium/lithium hydroxide battery carriers will not be able to compete on a dollar for dollar basis in the peaking market place through the year 2020. As further refinements are made, and if the larger OTEC plants are operated in clusters, the economics will improve. Further, there is the chance that combined peaking and intermediate generation could produce increases in battery utilization factors which would yield more competitive economics.

We are pleased to have the opportunity to be able to assist you in this effort, and will continue to do our best through the remaninder of this program. We are currently concluding the last areas of the remainder of the study (GE Subcontract 29412), and intend as part of the final report for that contract to review and modify, if necessary, the results presented here.

If you have any questions or comments which could be incorporated in the following report, please contact me or Mr. John Sinnott.

Sincerely,

Nicholas P. Biederman
Associate Director,
Energy Systems Analysis

NPB/yb

cc: Mr. R. F. Franciose, GE, Santa Barbara
T. J. Parkes, IGT
S. Davis, IGT

APPENDIX TO LETTER REPORT.
ERDA Sites for Plants

Location	Distance Offshore (N. Mi.)	Seasonal Variation Capacity Factor Correction	Net Capacity Factor
Key West	40	.8341	.750
Florida, W. Coast	160	.8000	.720
Miami	<10	.8816	.792
New Orleans	50	.7029	.630
Brownsville	100	.7080	.635
Puerto Rico	3	.8725	.785
Hawaii	1	.9025	.812
Brazil	>200	.8837	.793

PEAKING MARKET PROJECTIONS
(OTEC Capacity Required in GW, Assuming 50% Energy Efficiency)

	1990	2000	2010	2020
Cumulative Additions to Peaking Capacity from 1990				
High	Start	124	280	460
Low	Start	58	126	198

Assumed Peaker Operating Hours = 1140 Hours/Year

	1990	2000	2010	2020
Annual Peak Load Generation By Peaking Units Added After 1990				
High	Start	142×10^3	320×10^3	525×10^3
Low	Start	66×10^3	144×10^3	226×10^3

Source: G.E. Tempo, E. Tschupp.

APPENDIX B

OTEC COST REDUCTIONS RESULTING FROM TECHNOLOGY DEVELOPMENT AND EXPERIENCE

Estimates of early prototype costs of almost all innovations are higher than the costs expected when the product in mass production. Frequently, the early production cost is greater than the price of competing products; in making a decision to enter a market, industry must rely with some confidence on a cost trend that will reduce costs to a competitive and profitable level before negative cash flows (investment) become exessive.

Advanced energy conversion means, such as the various forms of solar energy: photovoltaic, solar thermal, and OTEC have this problem. The current state of the art, used to estimate prototype costs, will not give a cost competitive with the projected fossil and nuclear generation even in the face of rising fuel costs. However, once OTEC units are in production on a continuing bases it can be expected that their costs will reduce. Historic trends in related types of products can aid in estimating the amount of production required, to produce a competitive cost reduction, and the amount of investment required to reach this point. The amount of investment required may be excessive for a single firm to consider so that consortia of firms, and joint support by industry, customers, and government are used to share the risk and the investment burden. Nuclear power and military/commercial aircraft are examples where shared investment has bridged the gap to where production costs are competitive.

Trend data on production costs received much attention during and after World War II under the name "learning curve." The emphasis was on the observed fact that the production cost, and particularly the direct labor cost in man hours required per aircraft, tank, or other equipment, declined in a predictable way. The direct labor cost per unit varied with the cumulative production of the product or model as:

$$\frac{C_n}{C_{n_0}} = \left(\frac{n}{n_0}\right)^k$$

which on log-log coordinates as a straight line of slope -k. Here n is the cumulative production to date, n_0 may be 1 or some low production level by which start-up problems have subsided, and C_n and C_{n_0} are the direct labor cost of units n and n_0.

The learning curve was often described by the factor m by which cost declined for each doubling of cumulative production to date. This factor M is related to k, by $M = 2^{-k}$, or $C_n/C_{n_0} = (n/n_o)^{\log M/\log 2}$. The literature of that period indicated values of m for various production aircraft of 0.6 to 0.95.

COST REDUCTION MECHANISMS

To understand the factors that will reduce costs the development of production technology must be analyzed. Two different types of process are usually simultaneously active to reduce costs in any production industry. These are:

- Technological Innovation
- Experience related improvements

Technological innovations are those which physically change the production process ie. going from the open hearth to the Bessemer process for making steel. Experience related improvements are those which do not change the basic process but reduce costs by improving the process by such devices as parts standardization, improved jigs etc.

The most rapid cost reductions are usually associated with production technology innovations. In fact, in the computer industry technological innovation produced such large and frequent cost reductions that the name of "product generation" was coined and the concept is useful here in estimating the cost reduction possibilities.

A generation is defined as the lifetime of a product line or process which is based on an innovation resulting in a "quantum leap" or step-function improvement in performance over previous processes. Within a generation, incremental improvements will occur; but, between generations the differences in performance are large enough to separate into two classes. In essence, the length of generation is a measure of the rapidity of technological change. In the computer industry, for example, an improvement factor of five or more in the performance to price ratio has accompanied each new product generation.

The utility of this generation concept is that it allows an analyst to distinguish between changes which incrementally affect a production technology level and those which represent "technological breakthroughs". Innovations of production technology do not incorporate the future technology. In fact, they embody the know-how at the time when the decision to enter design and development was made. Reference to Figure B-1 may elaborate this conclusion. The figure uses 5 year production life for each product generation and two year spans for design and development. These durations have been characteristic of the computer industry and are used here for illustrative purposes.

The smooth curve labelled state-of-the-art research indicated the approximate performance (according to some measure) achieved in continuing laboratory research undertaken by manufacturers. The curve is actually a composite of multiple research achievements which together can be represented by the smooth envelope curve.

On this curve is a point which a manufacturer freezes the state-of-the-art and begins actual systems design development. The horizontal line extending to the right from this "freeze" point represents the basic state-of-the-art of the new generation. As indicated, the technology incorporated into commercial production will be at least two years* behind the state-of-the-art in research by the time production unit number one rolls off the line. Subsequent product cost improvements in the generation can be expected to result from experience related improvements.

* Timing will vary from industry to industry, but in all cases a lag will exist.

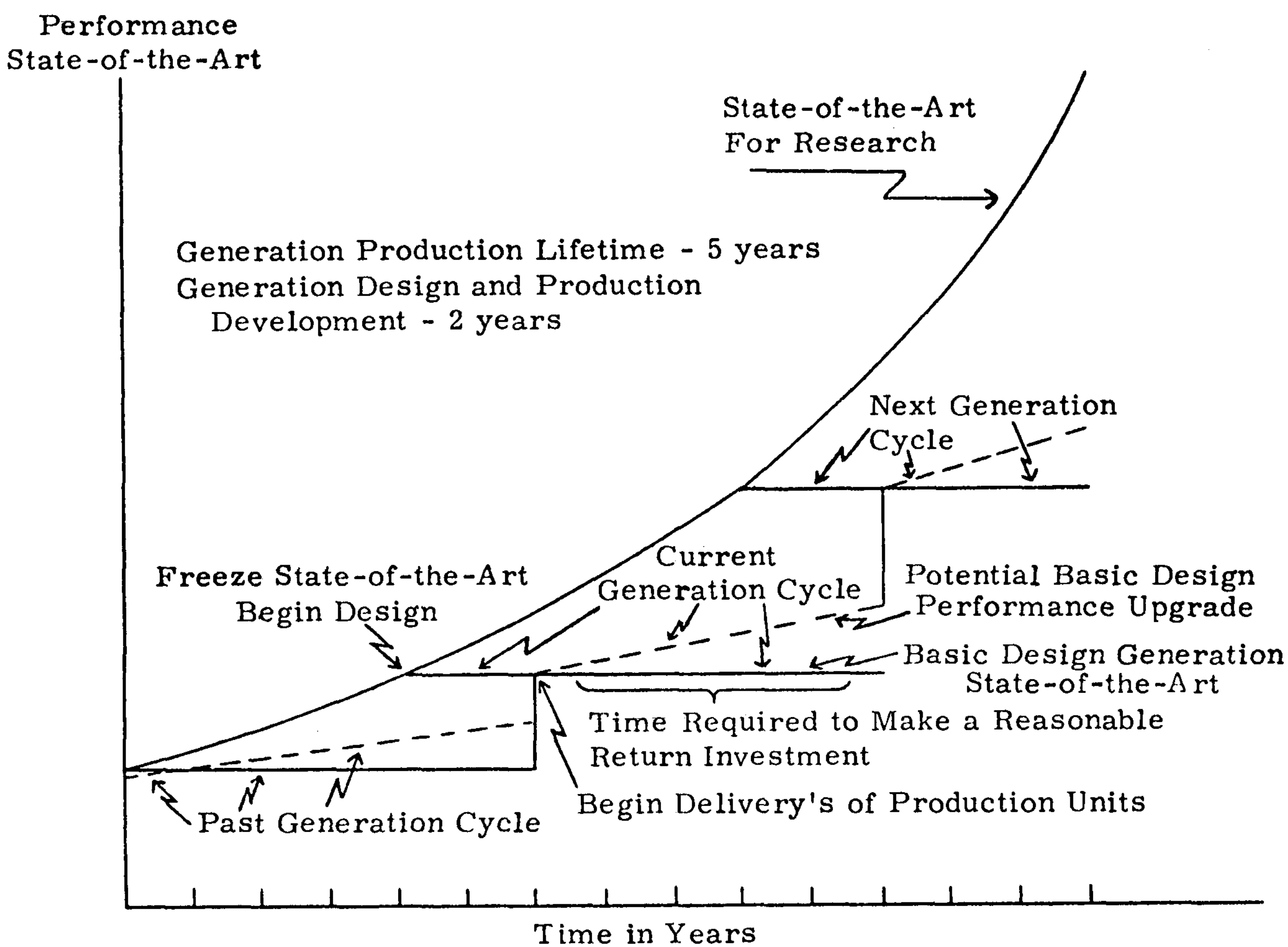


FIGURE B-1 - GENERATION CYCLE DIAGRAM

as shown by the dashed line. Meanwhile, basic research is driving up the state-of-the-art curve.

This diagram suggests that there are trade-offs associated with the timing of an innovation. From the manufacturers point of view, if he innovates a production technology as soon as it is proven by research he acquires the highest state-of-the-art and can enter the market with less competition. However, because the product line has not yet been in operation there is great risk of the product performance not meeting goals expected, and of production costs being higher than anticipated. If, on the other hand, the manufacturer waits until someone else innovates to get a production technology which has already been proven he may be accepting entering the market in the middle or end of the product generation, and be unable to recover his investment before the next generation is introduced.

The diagram also indicates that if one desires cost reduction, he is forced to provide continuing R&D into further technological developments. If he is to move along the basic research curve - i.e., acquire the technology for the next generation - he must conduct an intensive research program which builds on the knowledge already gained.

On the other hand, experience improvements in costs are usually easier to accomplish and cheaper. In industry a firm usually will not innovate a new production process until they have recovered their investment on the current production process.

If a government agency wishes to maximize cost reduction in the unit cost it must do two things:

- Encourage the research that will develop product and production technology innovations.
- Establish conditions where the manufacturer can rapidly recover his investment in the production facility so that he can start a new "Generations" production without financial loss.

COST REDUCTION RATES

Some perspective on the values of M (the rate of cost reduction) found for a wide range of components and products, and the factors governing the shape of the curves are best explained using Figure B-2. A number of actual experience curves from various sources are approximated by straight lines that closely match the actual point data. The curves, identified by numbers, represent:

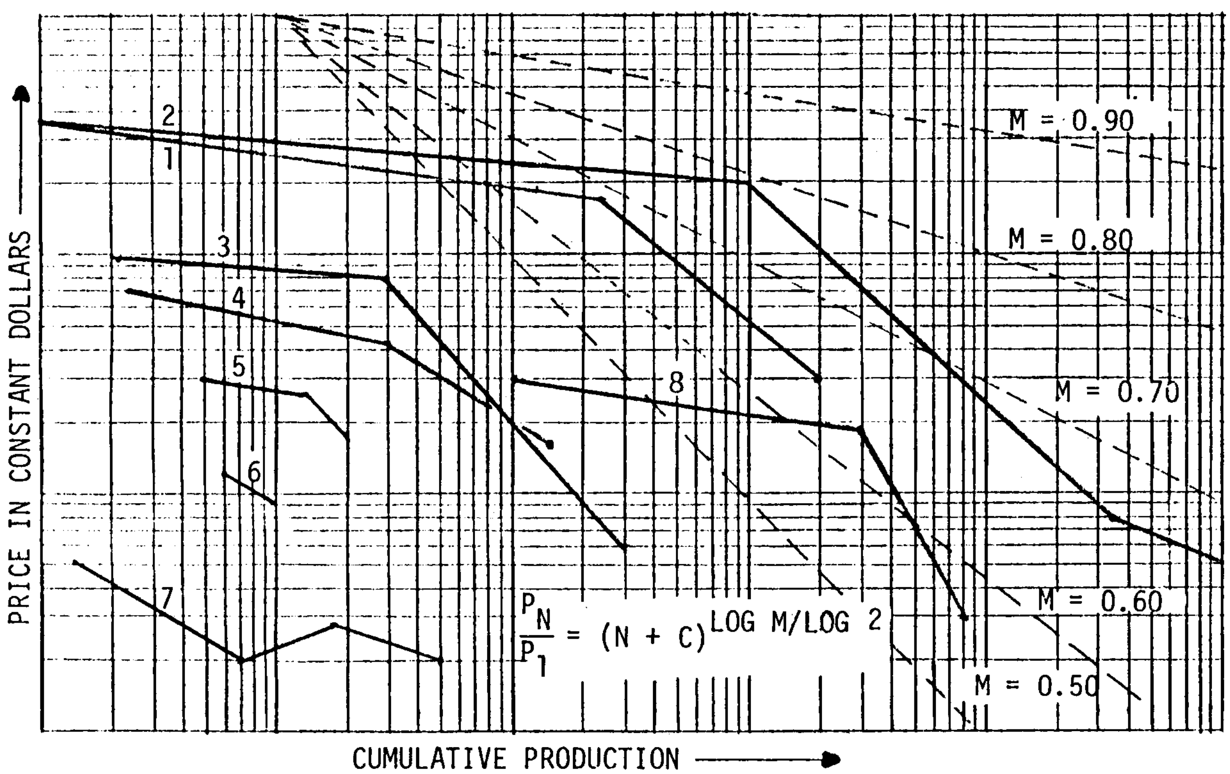


FIGURE B-2 - EXAMPLES OF PRODUCT PRICE REDUCTION WITH CUMULATIVE PRODUCTION

1. Germanium Transistors
2. Silicon Transistors
3. Germanium Diodes
4. Low Density Polyethylene
5. Free Standing Electric Ranges
6. Refined Sugar
7. Primary Aluminum
8. Photovoltaic Cells

That is, a variety of materials, components and consumer products. Most of these curves come from the Boston Consulting Group which treats the experience curve as an important management tool to be used in planning, in investment decisions, and in pricing policies. Since the production quantities and unit prices vary widely for these examples the scales should be considered as relative.

Some general observations about these curves are that it is not unusual to have more than an order of magnitude drop in price over many doublings, but seldom two orders of magnitude. There are undoubtedly exceptions in the computer field where the cost per multiplication or per memory cell has declined by many orders of magnitude over several generations of technology changes. Many of the curves have regions where the slope M is steeper than 0.70. These are often preceded and sometimes followed by regions with M between 1 and 0.9. For guidance the slopes M = 0.90, 0.80, 0.70, 0.60, and 0.50 are shown.

Users of the experience curve as a planning tool warn against expecting a steep curve to start with unit 1. The first 10 or 20, or thousands in the case of small components, may be erratic and both increase and decrease in cost. They are a small statistical sample, design changes are likely, mistakes are made and corrected, and research and development costs are fairly arbitrarily allocated among them. Another perhaps more significant cause of an almost flat region in early production is that many parts of the product are not completely new. They may represent prior experience that effectively makes them unit 10, 100, or 1000. The first 100 units produced, which represent over six doublings starting from unit 10. one from 100, and a small fraction of a doubling from unit 1000. However, going from unit 1000 to unit 8000 represents almost three doublings for all of these parts.

Stanford Research Institute has suggested that:

$$\frac{P_N}{P_1} = (N + C)^{(\text{Log } M/\text{Log } 2)}$$

is often a better fit. Here P_N is the price of the unit N (or C_N for cost), and a constant C has been added to indicate that the average effect of prior experience is equivalent to starting with unit (C - 1).

Also observable on curves 2 and 8 is an eventual leveling off, ie., decrease in slope.* The occurrence of technological breakthroughs are undoubtedly one cause of cost reduction. A fairly smooth curve may reflect many small improvements; a major breakthrough in a component that represents a large part of the system cost causes a steep region. As the cost of this system component is reduced to where it is no longer a dominant part of the cost, a return to the smooth curve of accumulated minor improvements can be expected.

Additional data exists which shows that within an established industry innovations can produce slopes as great as 60% to 65% for short periods. Figures B-3, B-4, and B-5 (MITRE) show curves of product prices as a function of accumulated production which show the effect of introduction of new production technologies.

OTEC PROJECTIONS/MARKETS REQUIRED

To assess the opportunity for cost reduction the OTEC components were examined to identify components that would offer opportunities for production technology innovations. Table B-I indicates the sensitivity that has been assumed for OTEC components. Those components with low or moderate sensitivity to technology development were assumed to follow a 90% cost reduction curve and those with a moderate sensitivity were assumed to follow a 75% cost reduction curve.

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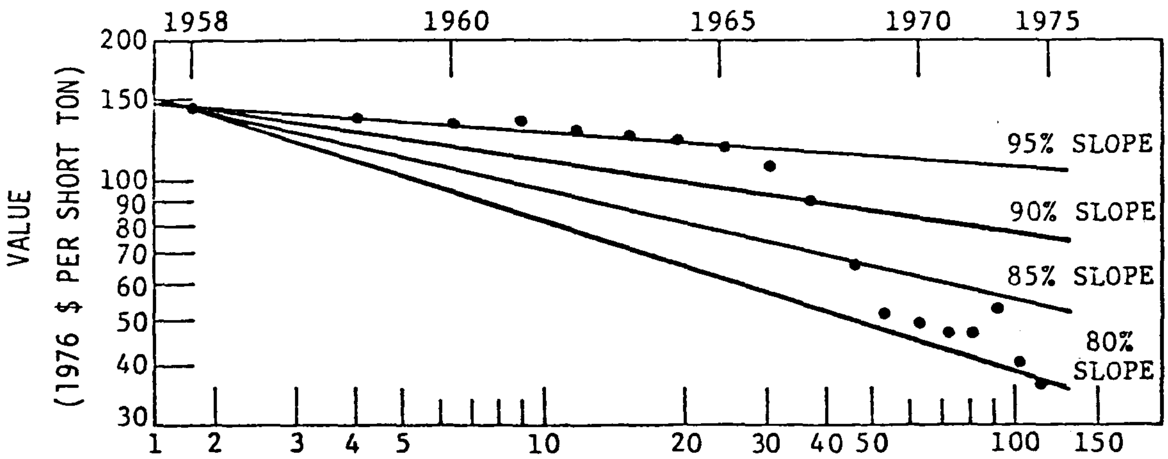
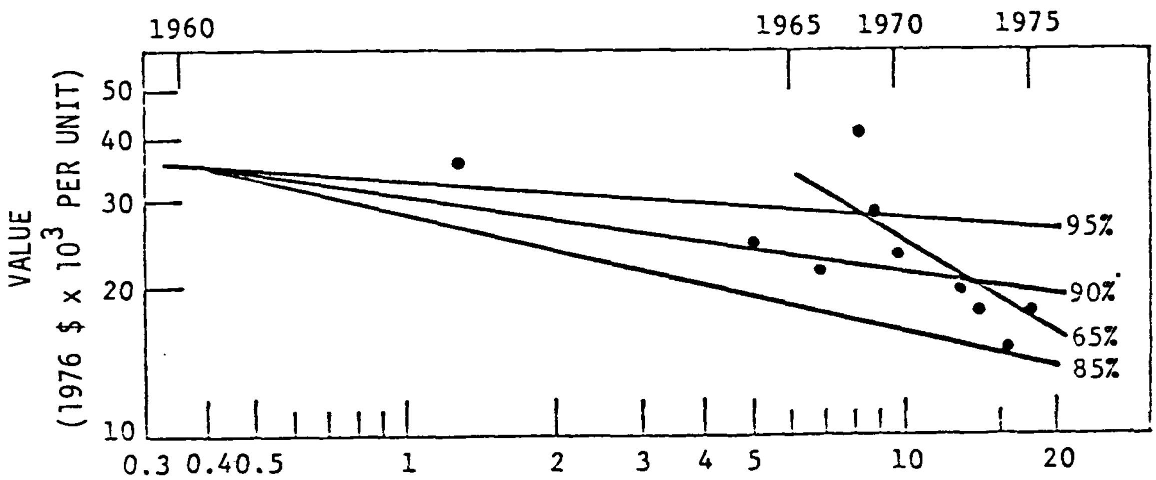
* The anomalous rise and fall for aluminum is not explained. Since most of these show price rather than cost, this may represent market fluctuation rather than cost changes.



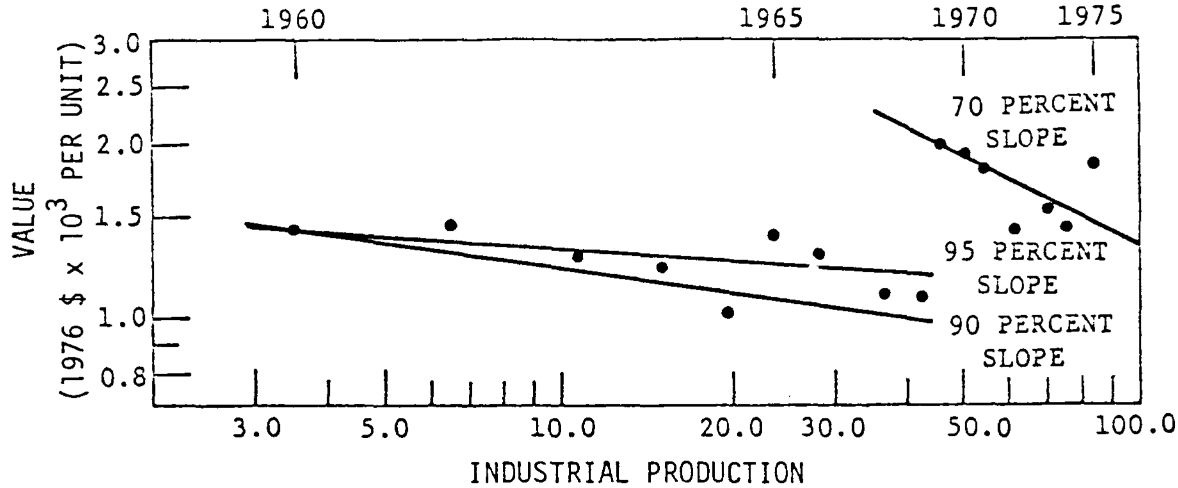
INDUSTRIAL PRODUCTION,
ACCUMULATED VALUME (SHORT TONS x 10^6) 1958 - 75
EXPERIENCE CURVE: AMMONIA (ANHYDROUS), 1958-1975

FIGURE B-3



INDUSTRIAL PRODUCTION,
ACCUMULATED VOLUME (UNITS x 10^3) 1960-75
EXPERIENCE CURVE: GENERATORS A.C., >400 kW, 1960-1975

FIGURE B-4



ACCUMULATED VOLUME (UNITS x 10^3) 1960-75

EXPERIENCE CURVE: PUMPS, CENTRIFUGAL >4 IN. OUTLET, 1960-1975

FIGURE B-5

TABLE B-1

OTEC COMPONENT SENSITIVITY

OTEC COMPONENT	TECHNOLOGY DEVELOPMENT	EXPERIENCE AND UPGRADING
HULL	LOW	MODERATE
COLD WATER PIPE	MODERATE	MODERATE
HEAT EXCHANGERS	MODERATE	HIGH
PUMPS	HIGH	HIGH
TURBINE-GENERATOR	HIGH	HIGH
MOORING	HIGH	HIGH
CABLE RISER	HIGH	HIGH
CABLE	LOW	MODERATE
SUPPORT	LOW	LOW

In the analysis OTEC components were aggregated into platform, power and mooring and transmission components and allowance was made for spares and interest during construction.

The platform group consisted of the hull or platform and cold water pipe. Under the assumption that the initial hull and pipe configurations would be made from reinforced concrete construction which is a fairly standardized shipyard construction process for producing large barges and/or large offshore platforms for use in the oil industry, as a result of the dominating cost of the hull it was assumed that the 90% learning curve would be most representative of this component group.

The power group was assumed to consist of the heat exchangers, sea water pumps, turbine and associated working fluid handling system and the generator. The heat exchanger shell and tube designs are moderately sensitive to technological development, while the shelless designs are highly sensitive. In addition materials options of titanium versus aluminum permit large cost variations. The ammonia turbine design will allow for considerable technology development and there are two options possible for the generator design. Production of AC generators in the OTEC size range is essentially a stable, mature technology. However, as OTEC units are deployed further and further offshore it will be adventageous to go to DC generation to reduce transmission losses and production of large DC generators in the OTEC size range is not a mature production technology. As a result a 60% experience curve was assumed to be representative for this group.

The mooring group would incorporate cable development, anchors and thrustors. Based on the current research on alternative approaches it was assumed that this group would also be sensitive to technology develpment and a 60% experience curve could be used.

The cable group would consist of the undersea transmission cable and the riser cable. In general, the major cost item in this group is the undersea transmission cable and its costs should dominate the group. At the present time, the bottom cable production technology and deployment is very well developed and there do not appear to be any technological developments before the year 2000 that would permit innovation in the fabrication or deployment or transmission mode. As a result this was assumed to have a 90% cost reduction experience curve due to the moderate sensitivity to experience and upgrading.

Spares were assumed to have an intermediate or 75% experience curve and the interest cost during construction had no cost reduction.

Table B-II below summarizes this discussion and indicates the aggregated cost reduction factor used.

TABLE B-II

COST REDUCTION EXPERIENCE FACTORS

OTEC COMPONENT	CONTRIBUTION TO COST	EXPERIENCE FACTOR	CONTRIBUTION TO AGGREGATED EXPERIENCE FACTOR
PLATFORM GROUP	31.5%	90%	28.4%
POWER GROUP	32.5%	60%	19.5%
MOORING GROUP	8.0%	60%	4.8%
TRANSMISSION GROUP	13.5%	90%	12.2%
SPARES	4.0%	75%	3.0%
INTEREST DURING CONSTRUCTION	10.5%	100%	10.5%
TOTAL	100.0%	——	78.4%

OTEC Prototype costs have been estimated to be between approximately $2200 and $1450 per kilowatt installed. Estimates of acceptable installed costs for commercial competitiveness indicate that a cost of approximately $800 per kilowatt would be required in the continental United States.

If we assume that the Department of Energy will order one gigawatt to be fabricated on the first set of OTEC production facilities established for all OTEC components purchased to assure the manufacturers that they will recover their investment it is possible to determine how much accumulated production will be required to bring OTEC costs down to the competitive range by the year 2000.

For a prototype cost of $2200 per kilowatt cumulative production of 16 GW and for a prototype cost of $1460 per kilowatt approximately 6 GW would be required. This is a large range for achieving competitive costs but, this range is within the limits of reasonable production requirements in a 10 year period. At 250 megawatts per OTEC unit this would be a maximum of 64 units and a minimum of 36 - if larger units are decided upon as the preferred size there would be fewer. The 64 unit production in the ten year period with a 2 year construction time would only require 13 production lines continuous operation and the 36 units would only require 7 production lines.

APPENDIX C

AN ESTIMATE OF THE COST TO CONSTRUCT A ONE·PERCENT OTEC DISCHARGE OPEN SEA MARICULTURE FARM

OPEN SEA MARICULTURE FARM

prepared by

M. J. Engel
Environmental Technology Section
GE-RESD, Req. No. K10

for the

Center for Advanced Studies
GE-TEMPO, Cont. No. 29403

DEC. 2, 1977

OTEC-OPEN SEA MARICULTURE FARM CONCEPT

The scope of this study is to:

1. Define a concept for structuring an OTEC (Ocean Thermal Energy Conversion) open-ocean mariculture farm to be used in the production of phytoplankton and a species of phytoplankton nurtured shellfish based on:
   (a) The work as reported by Laurence and Roels in their final report to ERDA, dated 8/76, entitled "Marine Pastures: A By-product of Large Floating Ocean Thermal Power Plants (COO-2581-03).

   (b) Utilization of one percent of the OTEC deep water discharge and assumption that the necessary pumping capacity is available on board the OTEC to move this amount of flow to a central distribution location sufficiently remote from the OTEC so as to not interfere in its primary function.

2. Develop a workable estimate, in some detail, of the cost (in current $) to engineer, construct and emplace such a farm - ready for operation.

The following brief discussion, tabulated cost elements, conceptual sketches, supporting computations and principal sources of information form an initial attempt to satisfy the needs of the planners and analysts at this stage of the activity.

The concept herein proposed, in view of the hostile nature of the open ocean environment, is essentially a tautly moored, highly compliant, closed bottom cluster of modular floating basins. A view of the farm from above is shown in Figure 1 and depicts an octagonal configuration occupying 65 acres (26 hectares) of ocean surface.

Triangular phytoplankton growing basins cover 40 acres (16 hectares), 5 acres each, at an average depth of 16,4 feet (5 m). Most of the internal more protected area is designated for producing the primary shellfish product. This amounts to approximately 3 acres (1.2 hectares). The remaining bounded surface serves as access ways for deep draft vessels and allows for freely compliant distortion of the growing basins in response to the variable ocean current and wind induced forces which prevail.

The structure also lends itself to being mechanically pulled beneath the surface in an emergency situation such as might occur when in the path of an impending hurricane.

Each distinguishable element is identified in relation to the items listed in the cost table. Refer also to Figure 2 which illustrates in generalized detail a cross-section elevation of the farm complex.

The Central Stalk buoy is the heart and spine of the system. This relatively large floating structure joins all of the farm elements together and houses the pumps, winches, flow distribution manifolds, servicing apparatus, power storage and conversion units, controls, recording monitors, data processing and communications gear.

Up-welled water from the OTEC - in this case, one percent of the projected discharge - is received at the stalk via twin 24" high density polyethylene pipes, at a rate of approximately 12,000 gpm. It would require 150 HP to move this flow from the OTEC to the stalk estimated to be 1/2 mile distant. This cost and the cost for the electrical energy via cable over the same path to power the distribution pumps, winches, hoists, other devices and power consumers are not included in the farm estimate. These items have been assumed to be a free by-product of the OTEC.

A total of 350 HP of pumping capacity would be needed to transport the OTEC water augmented by 25% warm local surface water (providing the 80/20 mix recommended) to the nutrient growing basins and back for distribution to the shellfish farm areas. This cost is assumed to belong to the farm.

Most of the items listed in the cost table in context with the concept sketches and supporting data sheets are hopefully self explanatory to the extent that they can be at this point of the development. Note, however, that in group D (Central Stalk), item D.6 "Other" is assigned a 20% (instead of 10%) factor to compensate for the greater uncertainty evident in estimating the preceding complex components of an as yet undesigned system. Further, the 25% contingency multiplier is superimposed onto the total cost summation in anticipation of the escalation which can occur between the presentation of the results of this exercise and the time when its implementation might be considered. The bottom line value of 22.5 million dollars which is thus developed is reasonable to assume for estimating purposes within the near time-frame.

SPECIFIC REFERENCES

1. Anderson, W., Ocean Research Equipment, Falmouth, Mass.
   (Sub-surface floats - B.3)

2. Damour, W. D., Watersaver Company, Denver, Col.
   ("Rubber" membrane - A.3)

3. Herchler, D. L., Pantasote Company of N. Y., Passaic, N. J.
   ("Rubber" membrane - A.3)

4. Langermann, P. H., Brockton Equipment Corporation, Boston, Mass.
   (Oil-spill booms - A.1)

5. Marston, M. W., Jos. T. Ryerson & Son, Philadelphia, Pa.
   (High density PE pipe - E.1, F.1)

6. Mostarda, M. S., IMODCO, Los Angeles, California
   (Mooring Systems, Spar buoys - B.1, B.3, D.1, D.2)

7. Smith, J., Mon Ark Boats, Monticello, Ark,
   (Utility boats - G.1)

8. Walker, J. J., Rep. for Carlisle Tire & Rubber Division, Carlisle, Pa.
   ("Rubber" membrane - A.3)

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4. Ocean Food and Energy Farm Project. Sub-Task No. 6: Systems Analysis, Vol. 2 Cultivation Subsystem. Final Report - Contract No. E (49-26) - 1027, ERDA, 7-1976

5. Open Sea Mariculture, J. A. Hanson, Ed., Oceanic Foundation, Hawaii, Dowden, Hutchinson & Ross, 1974

6. Preliminary Design and Cost Models for Spherical and Cylindrical Buoys for the Ocean Farm Project, H. A. Wilcox, U. S. Naval Undersea Center, San Diego, California, 2-1976

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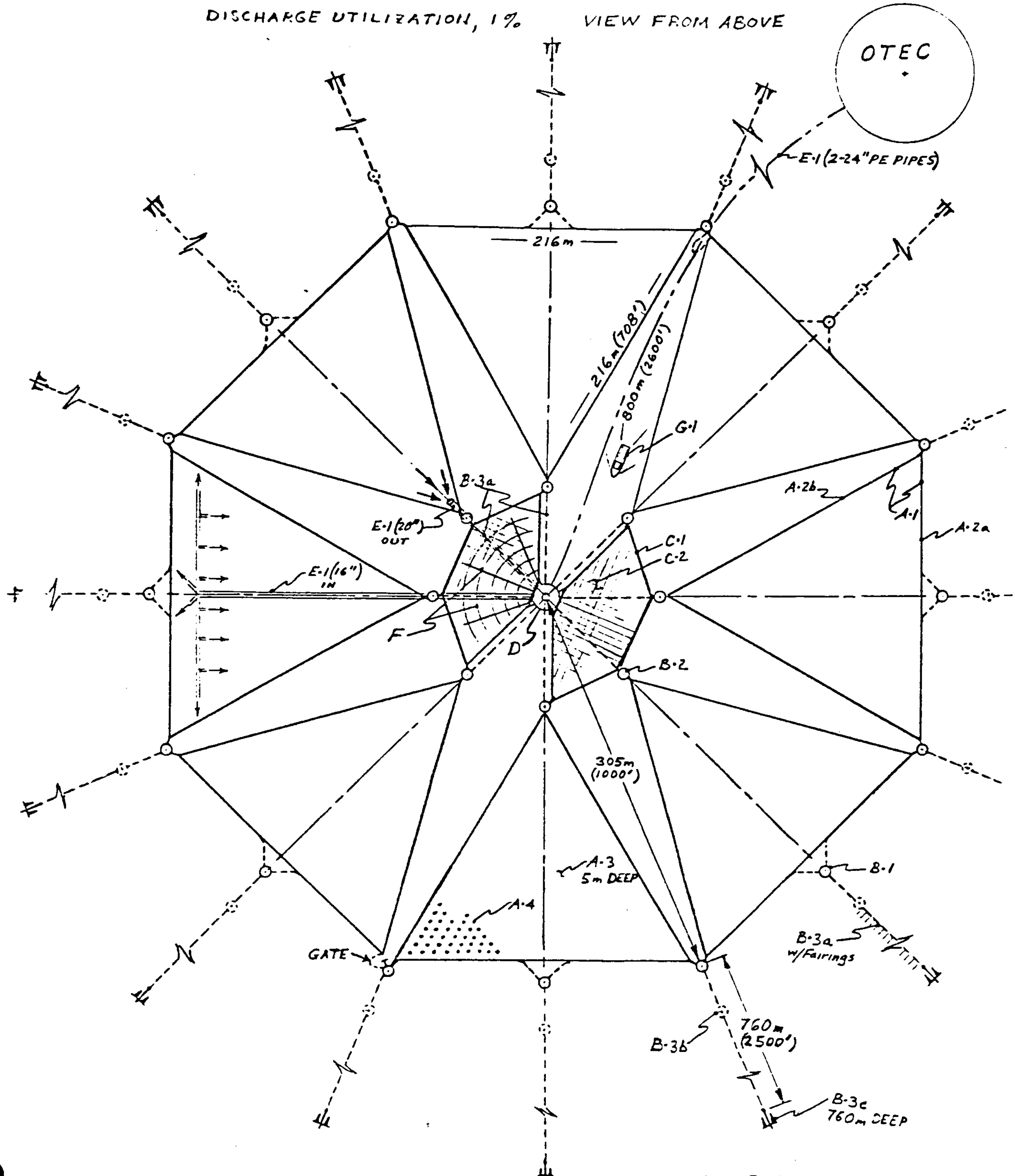
9. Standard Handbook for Mechanical Engineers (7th Ed), T. Baumeister and L. S. Marks, eds, McGraw-Hill, 1967

CONCEPT - OTEC MARICULTURE FARM

DISCHARGE UTILIZATION, 1%   VIEW FROM ABOVE



SCALE: 1 cm ≈ 36 m
1 IN ≈ 100 YD

12/1/77
M.J. Engel

FIGURE 1.

Concept – OTEC Mariculture Farm

CROSS-SECTION VIEW
W/ FLOW SCHEMATIC

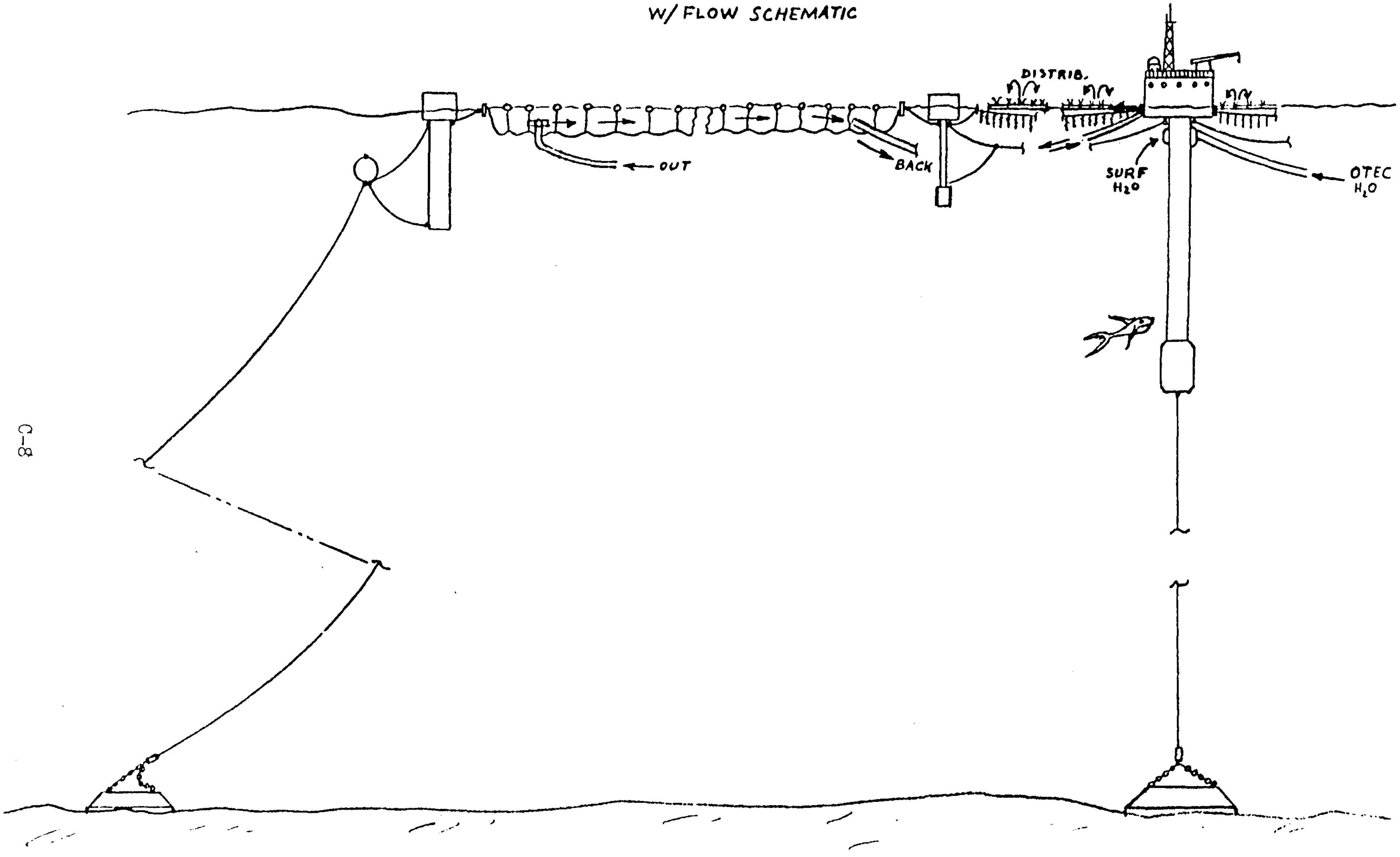


FIGURE 2.

NOT TO SCALE

12/2/77
m.J. Engel

OTEC, 1% DISCHARGE, MARICULTURE FARM

IDENTIFICATION & ITEMIZATION OF COST ELEMENTS

ITEM	MATERIALS/DESCRIP.	SIZE/IDENT.	QTY.	UNIT COST	SOURCE	OTHER INFO.	TOTAL COST (K$)
A. Nutrient Growing Basins							
1. Perimeter Flanges	Vinyl coated nylon fabric containment booms w/flotation & ballast	Spilldam Model 360 3'Hx1¼"T	17,000'	15	Brockton Equip. Brockton, Mass.	Compensate Ballast for Tension Line	255.
2. Perimeter Tension Line							
a. Outside Legs	Polyester/Polyester 2 in 1 Braided Rope	5" Ø	5,700'	24	Samson Cordage Boston, Mass.	S.G. 1.38 Good Abrasion	137.
b. Inside Legs		3¼" Ø	11,400'	11		Min. Stretch S.F.= 4 min.	125.
3. Flexible Membrane	EPDM w/Nylon Reinf.	0.060" T	$1.74x10^6$ ft^2	0.5	Carlisle Tire & Rubber Carlisle, Pa.	S.G. 1.18	870.
a. Piecing & Seaming	Assy from rolls	20'Wx100'L	$133x10^3$ ft	0.3			40.
4. Bedspring Floats	PU Closed Cell Foam Spheres 10#/ft^3	15" Ø	3,750	12.	Est. (10./ft^3+2. mold chg)	1 ft^3 ea.	45.
a. Mooring Line	Nylon/Polypro. 2 in 1 Braided Rope	¼" Ø	67,500'	0.07	Samson Cordage Boston, Mass.	Neut. Buoyant	5.
b. Attach. Fittings	Nylon/S'Stl	--	7,500	1.	Est. (2/Assy)	--	8.
5. Misc. Other Fittings & Connecting Hdwre	S'Stl/Galv Stl Monel/Plastics/Zincs	———	(@ 10%)	———	———	Rope, Terminations, Connecting Shackles, Rings, Chain, Sacrificial Anodes, Swivels, etc.	149.
							1634.

ITEM	MATERIALS/DESCRIP.	SIZE/IDENT	QTY	UNIT COST	SOURCE	OTHER INFO.	TOTAL COST (K$)
B. Support Posts							
1. Bedpost (Spar) Buoys	Struct. Stl (PU-foam filled) or Reinf. concrete w/Stl membrane seal and/or foam filled	16'Øx82'L	16	250K	IMODCO (SBBM) Los Angeles, CA Wilcox, USNUC San Diego, CA	--	4000.
2. Apex (Dumb-bell) Buoys	Struct. Stl (PU-foam filled) or Reinf. concrete w/Stl membrane seal and/or foam filled	16'Øx16'L w/50'Boom	8	100K	Est. (% B.1)	--	800.
3. Moorings							
a. Line	Nylon/Nylon 2 in 1 Braided Rope w/Anti-strumming Fairings	6"Ø	60,000'	30.	Samson Cordage Boston, Mass.	S.G.=1.14 Wet Wgt=1.17#/ft. S.F.=4.7	1800.
b. Sub-surf. Floats	Steel sphere O.R.E. Mod. SS-73	6'Ø	16	6.3K	Ocean Research Equipment Falmouth, Mass.	Net Buoyancy =4240 lb.	101.
c. Anchors & Chain Assys.	Steel/Concrete	170-ton Concrete "Boat" sunk in place	16	75K	Est. Fab. Concrete @ 0.20/lb. Fab. Steel @ 0.50/lb. Hdwre-Crosby -McMaster Carr	--	1200.
d. Swivels, Shackles, Thimbles, Rings	Steel	100-ton	16 sets	10K	Est.	--	160.
4. Misc. Other Items				(@ 10%)		Incl. Deployment gear, ship time (10K/da for 30 days), etc.	806.
							8,867.

ITEM	MATERIALS DESCRIP.	SIZE/IDENT.	QTY	UNIT COST	SOURCE	OTHER INFO.	TOTAL COST (K$)
C. Shellfish Grid							
1. Perimeter Line	Nylon/Polypro. 2 in 1 Braided Rope	2"Ø	2,200'	2.30	Samson Cordage Boston, Mass.	Neut. Buoyant	5.
2. Grid Line (1 meter spacing)	Nylon/Polypro. 2 in 1 Braided Rope	3/8"Ø	100,000'	0.13	Samson Cordage Boston, Mass.	Neut. Buoyant	13.
a. Attachment Hdware	Stainless steel	for 3/8"	13,000	2.	Est.	Hooks, snaps, etc	26.
3. Growing Cages/Surfaces	PP+PU Foam	5m. Deep	26,000	7.50	Est.	2xNo. req'd per planting	195.
a. Attachment Hdware	Stainless Steel	for 3/8"	52,000	2	Est.	Hooks, snaps, etc.	104.
4. Other Fittings and Installation	(@ 10%)						34.
							377.
D. Central Stalk							
1. Buoy Hull	Struct. Stl. w/deck and compartments for equip. & structure. Stability spar filled w/PU foam	33'Øx20'L upper 10'Øx144'L spar	1	400K	Est. based on IMODCO scale-up	--	400.
2. Mooring							
a. Line	Nylon/Nylon 2 in 1 Braided Rope w/Anti-strumming Fairings	7"Ø	2,400'	48.	Samson Cordage Boston, Mass.		115.
b. Anchor & Chain Assy	Steel/Concrete	250 ton Concrete "Boat" sunk at location	1	100K	Scale of B-3.C	--	100.
c. Swivel, Shackles, Thimbles, etc.	Steel	130 ton	1 set	20K	Est.	--	20.

ITEM	MATERIALS DESCRIP.	SIZE/IDENT.	QTY	UNIT COST	SOURCE	OTHER INFO.	TOTAL COST (K$)
D. (Continued)							
3. Structure	Steel Supports, Foundations, Bulkheads, Rails, etc.	--	--	--	Est.	--	50.
4. Mechanism	Winches, Cranes, Pumps, Conveyances, etc.	---	--	--	Est.	--	150.
5. Instrumentation, Communication, & Power Conditioning Gear	Sensors, Controls, Recorders, Alarms, Information Processors, Transformers, Cabling, Switchgear, etc.	--	--	--	Est.	--	100.
6. Other	——————	(@ 20%)	——————	——————	——————	Incl. Deployment Gear, Ship time, etc.	187.
							1122.
E. <u>Feedwater System</u>							
1. Pipe	HDPE	24" Sch. 40	5200'	20.	Phillips Driscopipe	--	104.
		20"	2400'	15.	J.T. Ryerson & Son		36.
		16"	6600'	10.			66.
		12"	4700'	7.			33.
		6"	2800'	3.			8.
2. Fittings	HDPE	Ell's, Tees, Flanges, Reducers, etc.	As Req'd (@ 10% of E-1)			--	25.
3. Valves	Plastic/Alum-Bz	24"	4	4K		--	16.
		20"	8	3K			24.
		16"	16	2K			32.
4. Structure & Flotation	Steel/Plastic		As Req'd (@ 10% of E-1, 2, & 3)			Reinforcing Structure, Riser Floats, Rope	34.
5. Other	——————	——————	(@ 10%)	——————	——————	——————	38.
							416.

ITEM	MATERIALS DESCRIP.	SIZE/IDENT.	QTY	UNIT COST	SOURCE	OTHER INFO.	TOTAL COST (K$)
F. Nutrient Distrib.							
1. Pipe	HDPE	12" Sch. 40 6"	5,000' 20,000'	7. 3.		--	35. 60.
2. Fittings, Nozzles & Manifolds	HDPE		As Req'd (@ 100% of F-1)			--	95.
3. Valves	Plastic/Alum-Bz	12"	24	1.5K		--	36.
4. Structure & Flotation	Steel/Plastic	--	As Req'd (@ 10% of F-1, 2, & 3) As E-4				23.
5. Other	——— (@ 10%) ———						25.
							274.
G. Support Equip.							
1. Tenders & Harvesting Boats	Alum	21' 32'	2 2	11.5K 20. K	MonArk Boat Monticello, Ark.	Shallow Draft	63.
2. Tools	Various	--			Est.	--	50.
3. Supplies	--	--			Est.	--	50.
4. Spares	--	--	(@ 5% of A thru F less B-1, 2 & D-1)				375.
							538.
H. Engineering, Logistics & Management							
1. Design	Man-power	Eng'g & Desr M-yr	12	83K	Local Rates	--	996.
2. Development & Test	a. Man-power	Eng'g & Tech, M-yr	10	75K	Local Rates	25% for Model & Small Scale Testing 75% for prototype evaluation	750.
	b. Mat'l & Sub-contracts	——— (@ 60% of 2-a) ———					450.
3. PC, QC & Admin.	Man-power	Support Functions	3	83K	Local Rates		249.
4. Transport to Site	———				Est.		500.

ITEM	MATERIALS DESCRIP.	SIZE/IDENT.	QTY	UNIT COST	SOURCE	OTHER INFO.	TOTAL COST (K$)
H. (Continued)							
5. Assy & Installation	a. Man-power	Trades M-yr	10	75K	Est.	--	750.
	b. Ship-time	Ship-days	30	10K	Est.	--	300.
6. Check-out	Man-power	Eng'g M-yr	3	83K	Local Rates	--	249.
7. Start-up	Man-power	Eng'g & Support	1	83K	Local Rates	--	83.
8. Other	(@ 10%)						433.
							4,760.
					Summation of All Elements		17,988.
					Contingency @ 25%		4,497.
					GRAND TOTAL		22.5M

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