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HYDROGEN GENERATION BY OTEC ELECTROLYSIS, AND ECONOMICAL ENERGY TRANSFER TO WORLD MARKETS VIA AMMONIA AND METHANOL

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Abstract—OTEC plantships sited in tropical oceans would generate 150–400 MWe (net) of low-cost electric power per plantship. These plantships would tap a virtually unlimited source of energy for economical production of hydrogen by water electrolysis. Hydrogen could be delivered to U.S. users from such plantships via hydrogen liquefaction, transport and storage, or by incorporation in a chemical carrier and shipment by conventional transport methods. Costs of OTEC energy in the form of liquid fuels delivered to U.S. users are estimated to be favorable compared with equivalents derived from land-based sources after 1990. The paper briefly reviews the status of OTEC technology and projected costs for plantship construction and deployment. This provides a basis for a more detailed description of the onboard processes and costs for production of hydrogen, ammonia and methanol on OTEC plantships. Estimated costs for the three fuels delivered to U.S. ports are: liquid hydrogen \$41–66 MBtu, ammonia \$10–16 $MBtu^{-1}$, methanol \$9–14 $MBtu^{-1}$ (1983\$). Production of OTEC methanol involves transport of coal to the plantship where it is oxidized to carbon monoxide with oxygen and steam followed by reaction of the gas mixture with added electrolytic hydrogen. The process efficiently uses both the hydrogen and the oxygen produced by onboard electrolysis of water.

INTRODUCTION

Ocean Thermal Energy Conversion (OTEC) is a technology which uses the solar energy stored in the surface waters of the tropical oceans to generate electrical power. The power may be applied on shipboard to operate a plant which produces fuels or chemicals, or at suitable sites the electric output can be cabled ashore to provide power for local utilities.

The solar energy incident on the tropical oceans during a day averages approximately 20 billion kilo joules per square kilometer, which corresponds to an average 24-h rate of 230 MW km^{-2}. The radiation warms the water within a depth of 50 to 100 meters from the surface to a temperature of 27–30°C, but at 1000 m depth the temperature is 5°C or less. Thus an average temperature difference of 22–25°C is available 24 hours a day, 365 days a year for OTEC power generation. Engineering analyses confirmed by experiment show that with this temperature difference approximately 3% of the heat in the warm water which passes through the heat exchanger of an OTEC power system can be converted to net electrical energy.

The acceptable upper limit for continuous OTEC power production from the oceans has not been determined but consideration of the radiation, aerodynamic and hydrodynamic energy balances at the ocean surface leads to an estimate that extraction of at least 0.2 MW of net OTEC power per square kilometer of tropical ocean could be sustained indefinitely without significant predicted impact on the oceans physical or biological characteristics [1, 2].

Thus if OTEC plants were sited at appropriate spacing throughout the total tropical ocean area suitable for OTEC power generation (approx. 60 million km^2) the OTEC power that could potentially be generated would exceed 10 million MW. This is forty times present U.S. electric power consumption and an ample resource to provide a sound base for an eventual 'hydrogen economy'.

As shown in Fig. 1, if the potential OTEC power were used to electrolyze water, and the hydrogen and oxygen produced were used onboard as feedstocks for ammonia or methanol production, the output would far exceed in heating value the present total energy demand of the U.S.

The use of OTEC, in combination with water electrolysis, to supply fuels and other products which could reduce world dependence on diminishing petroleum reserves has been the subject of continuous investigation at APL since 1973. These studies have shown that OTEC plantships of 100–400 MWe net output at the busbar, which would be comparable in size with super tankers, would be most cost effective.

Engineering analyses of the OTEC system indicate power could be generated on plantships of this type at estimated costs low enough to permit fuels and other products made onboard to be delivered to land based users at prices competitive with products available via conventional methods of production from fossil fuel or nuclear sources.

The advantages of using OTEC power to produce hydrogen fuel by onboard water electrolysis were recognized at the start of the OTEC program [3] and have

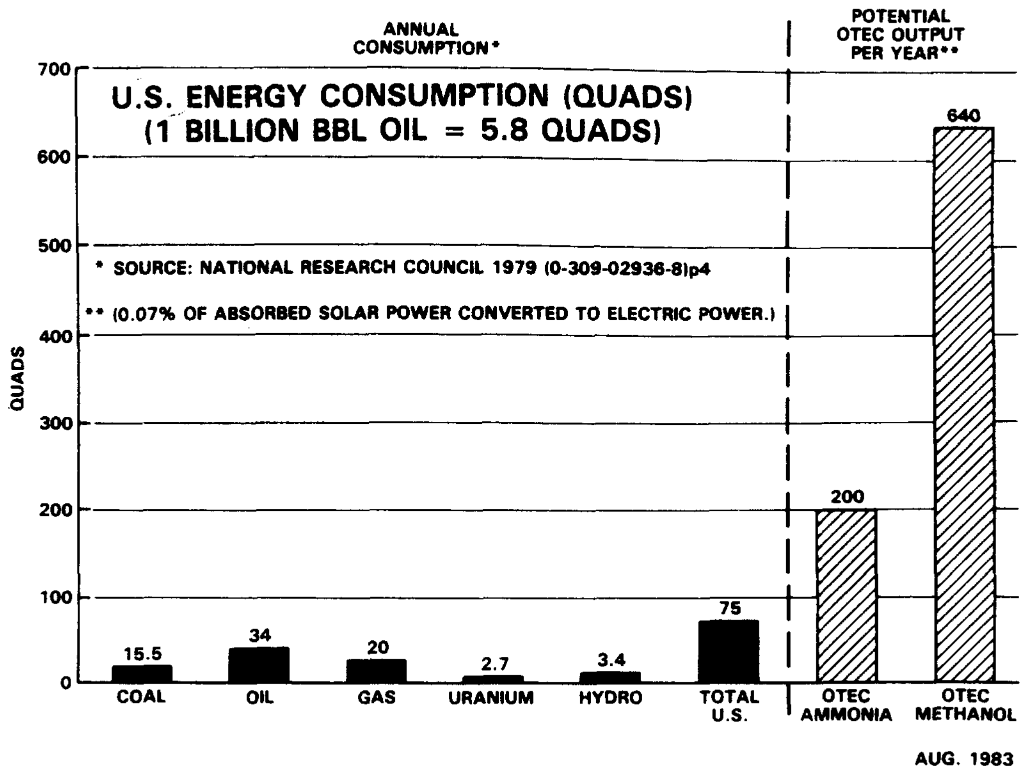

Fig. 1. U.S. energy consumption (quads). (1 = 10^{15} BTU = 1.055 × 10^{15} kJ = 172 million bbl oil).

been studied in some depth. However, the difficulties and costs of storing and transporting hydrogen as gas, hydride or liquid led us to consider combining the hydrogen with nitrogen extracted from the air, to form ammonia (NH_3) onboard the OTEC ship as a more attractive product.

Recently, economic considerations and the national need for an automobile fuel that can substitute for gasoline made from petroleum have focused our investigations on OTEC-produced methanol as an attractive candidate. Methanol would be synthesized on board the OTEC plantship in a process which would efficiently use the oxygen and hydrogen produced onboard by electrolysis in combination with coal transported to the ship, to form methanol (CH_3OH).

The OTEC plantship processes, the delivered product costs and potential contributions to future world fuel supplies by hydrogen, ammonia and methanol are discussed in the following sections.

HYDROGEN

Hydrogen generation via water electrolysis provides a highly efficient way to convert the electrical energy output of the OTEC power plant to chemical enthalpy. With electrolysis cells now being developed efficiencies of 85% to 90% are projected [4].

A schematic diagram for OTEC hydrogen production, liquefaction and shipment based on a 40 MWe (nom) plantship sited in equatorial waters is shown in Fig. 2. The plantship would produce 15.5 metric tons per day of liquid hydrogen, and at 345 days per year operation would deliver an annual average of 14.9 mt d^{-1} or 14.6 mt d^{-1} after 2% boil-off in transit, of liquid hydrogen to mainland ports for storage or use.

The estimated plant investment, operating cost and delivered hydrogen costs for this system are presented in Table 1. Costs for electrolysis, liquefaction and storage are based on [5]. The remaining costs are taken from a recent APL conceptual design study of the possible use of OTEC hydrogen to supply fuel for the NASA shuttle [6]. Costs are stated in mid-1983 dollars, with appropriate corrections for inflation since 1980. The cost uncertainties stated in this table and in Tables 2 and 3 are based on an estimate for each subsystem of the degree to which it is available from current sources. Components available off the shelf at fixed cost and delivery are assigned a 10–15% uncertainty, those available with current technology but which would require redesign or moderate scale-up are given a 20–25% uncertainty, components requiring major scale-up or that would depend on undemonstrated technology such as deployment of the full-size cold-water pipe are assigned a 100% uncertainty. Potential savings

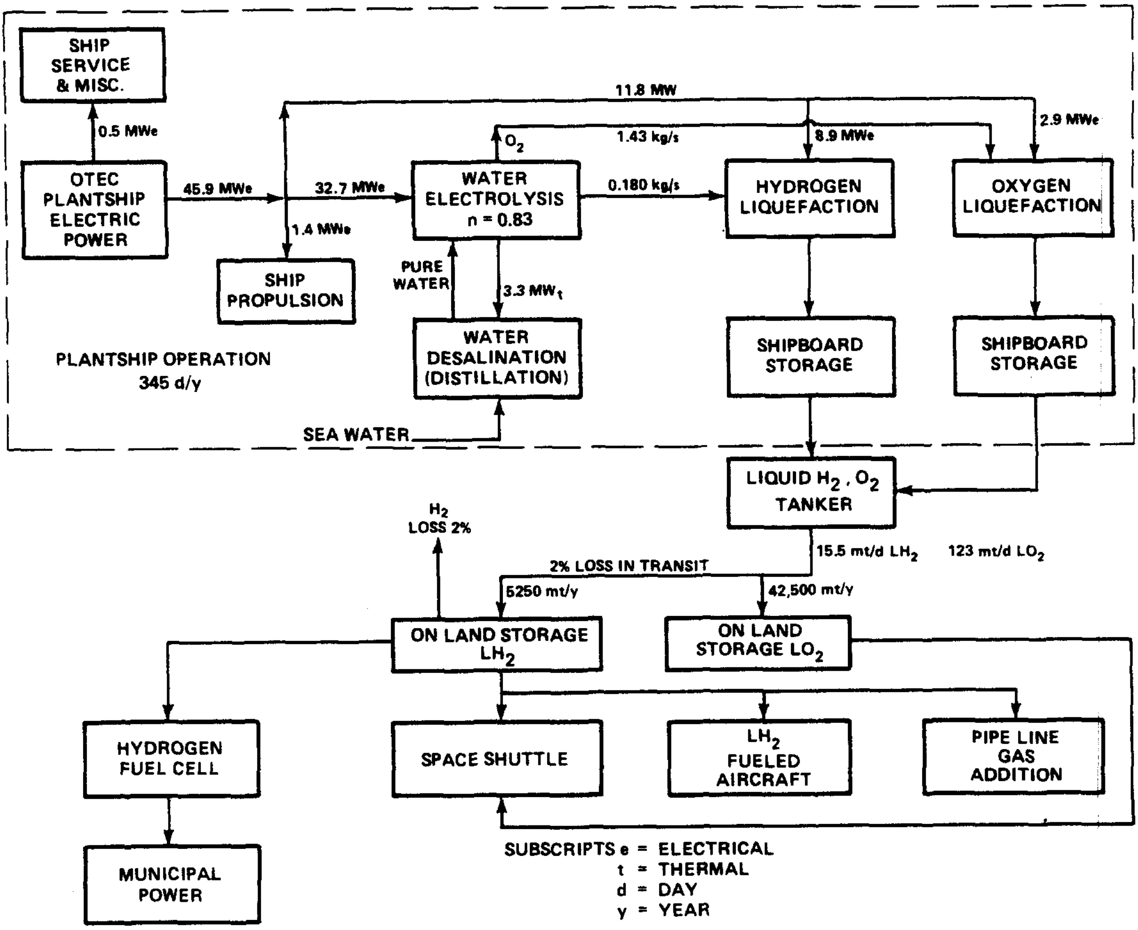

Fig. 2. OTEC liquid hydrogen plantship.

reflect cost reductions expected from purchase of multiple identical units such as pumps and heat exchangers, and from system state-of-the-art improvements now underway such as more efficient and lower-cost heat exchangers, electrolyzers, processes and total system optimization. Listed costs are for the first unit. Further cost reduction of up to 30% is projected for the eighth plantship of each type.

Table 1 shows that the projected cost for OTEC liquid hydrogen as estimated for this state-of-the-art plantship would be roughly twice as high as that from a 12 mt/d land-based plant using methanol as hydrogen source [7]. Larger scale OTEC hydrogen plantships would offer substantial savings through economies of scale and learning curve benefits of modular systems just as for the ammonia plants discussed later.

AMMONIA

Ammonia is formed by the catalytic combination of 3 mol of hydrogen with 1 mol of nitrogen at high pressure and moderate temperature in the presence of an iron oxide catalyst. Under these conditions a mixture at chemical equilibrium is formed which contains nearly pure ammonia. If the temperature is raised and the pressure lowered the hydrogen and nitrogen are regenerated. Since the reaction is an equilibrium process with little heat evolution it provides an efficient method of storing hydrogen. Thus the process involving electrolysis of water followed by ammonia synthesis can convert up to 80% of the OTEC electrical energy to chemical energy stored in the form of ammonia.

Ammonia is easily liquified, can be stored at room temperature at moderate pressure and may be transported in existing ammonia tankers, trucks, tank cars and pipelines. Liquid ammonia contains significantly more hydrogen per liter than an equivalent volume of liquid hydrogen or metal hydride. (The weight of hydrogen in liquid $NH_3 = 0.136\ kg\ l^{-1}$, in $LH_2 = 0.071\ kg\ l^{-1}$, and in Mg_2Ni hydride $= 0.066\ kg\ l^{-1}$.

Ammonia has been demonstrated to be an excellent fuel for vehicle or industrial uses, and with appropriate

Table 1. Estimated cost of OTEC liquid hydrogen (1983$).

	40 MWe (nom), 46.4 MWe (net) LH_2 Plantship		
Plant investment	Nominal cost ($M)	Potential savings (%)	Potential overruns (%)
Basic plantship	140.0		
Platform system	60.1	13	16
Hull	28.4	15	20
Pumps & distribution	11.1	15	15
Position control	9.6	10	10
Outfitting, furnishings and other	10.0	10	10
CWP system	10.7	25	100
Power systems	47.4	24	18
Heat exchangers	35.8	28	20
Power conversion	8.7	10	10
Other	2.9	15	15
Deployment services	13.3	31	82
Platform	1.5	15	15
Power system	1.3	15	15
CWP	10.5	35	100
LH_2, LO_2	56.5	24	25
Desalination plant	0.7	15	15
Water electrolysis plant	13.7	30	35
H_2, O_2 liquefaction	21.7	25	25
Additional power conversion	7.0	10	10
H_2, O_2 Storage piping compressors, utilities	5.4	25	25
Load, transfer equip, other	8.0	25	25
Acceptance, Ind Fac E&A	8.5	20	20
Estimated direct cost	197	21 (av)	28 (av)
Interest during constr (14.8% of direct cost)	29		
Total plant investment (PI) ($M)	226	170	274
Annual cost ($M)			
Real fixed cost (0.059 × PI)	13.3	10.6	16.2
Annual O&M	5.7	4.8	7.1
Shipping $.13 l^{-1}	6.4	5.8	7.6
Total ($M)	25.4	21.2	30.9
Annual production (mt) minus boil-off	5240	5320	5010
Cost at U.S. port ($ mt^{-1})	4850	3985	6170
Sales price at U.S. port ($$mt^{-1}$)	6990	5500	8870

Note: the cost corresponds to the return on equity that will amortize the plantship in 25 y and pay 7% per year to the shareholders on their equity. The sales price is the value that will return a profit of 25% per year after taxes on the common stock. The calculation is based on the formulas developed in the EPRI Technical Assessment Guide P-2410-SR, May 1982. The 'real cost' is defined to be the levelized cost corrected for inflation, i.e. in constant dollars.

Costs and prices derived by these formulas are presented for purposes of general comparisons. They are not valid for individual cases which will involve licensing, interest, financial planning arrangements, negotiated sales contracts and government regulations.

combustion conditions produces only water and nitrogen as products. Thus it is an attractive candidate for a future fuel that would eliminate the 'greenhouse effect' and could be produced by OTEC in quantities sufficient to meet world needs.

Ammonia is currently produced in large quantities in the U.S. (~18 million ty^{-1} for use as a feedstock for nitrogen fertilizers and plastics manufacture. The current process requires the use of 1090 m^3 (38 500 ft^3.) of natural gas, as a source of hydrogen, per tonne of ammonia produced. Because of the large demand, facilities for ammonia transport, storage and distribution already exist which would facilitate its entry as a future replacement for carbon containing fuels.

The initial studies of ammonia synthesis on OTEC plantships, [3] indicated that this method of production could lead to delivered costs below those expected in the mid-80's for ammonia produced from natural gas at decontrolled prices. Accordingly, with the support of the U.S. Department of Energy, a preliminary engineering design of an ammonia plantship was undertaken to provide reliable information on the ship and process layouts from which industrial estimates of cost could be developed [8].

Design effort was concentrated on a demonstration size OTEC plantship that would generate 40 MWe (net) of OTEC power at the onboard busbar. The power would then be used for water electrolysis to supply hydrogen for ammonia synthesis. Part of the OTEC power would be used to operate an air liquefaction plant for nitrogen production, and additional energy would be devoted to ship propulsion and hotel requirements. A schematic of the process is shown in Fig. 3.

The engineering design study, [8], provided detailed information on the OTEC platform, power plant, cold water pipe and other components. Structural, layout and performance requirements were defined from which detailed construction and operating costs could be estimated. This information has been used as a basis for estimating costs for the 325 MW OTEC plantships, which would produce 1000 tonne per day of ammonia. Full details are presented in [6].

A summary of the cost estimates for the 40 MW demonstration plantship and the scale-up to 325 MW are presented in Table 2. Costs are updated to January 1983 dollars using a factor of 1.14 relative to 1984, as listed in the producer price index for industrial commodities, U.S. Department of Labor, Producer Price Index, January 1983.

The comparison, presented in Table 2, of the estimated delivered price of ammonia from the eighth 325 MW OTEC plantship (\$260–\$345 mt^{-1}), with the June 84 U.S. ammonia wholesale price of \$209–220 mt^{-1} shows that OTEC ammonia would not be cost competitive with ammonia derived from natural gas at current prices. However, because of decontrol, gas prices have been increasing toward parity with oil on a heating value basis and may be expected to reach that level by the early 1990's when commercial operation of OTEC ammonia plantships can be envisaged. If the real price of oil increases at 1 to 2% y^{-1}, as current wisdom forecasts, natural gas would cost \$0.19–0.22 m^3 in 1990 and the ammonia price would reach \$275–330 mt^{-1} (in early 1983 dollars). At this value the projected cost of OTEC ammonia would be sufficiently attractive to warrant significant industrial interest in the development of OTEC ammonia plantships.

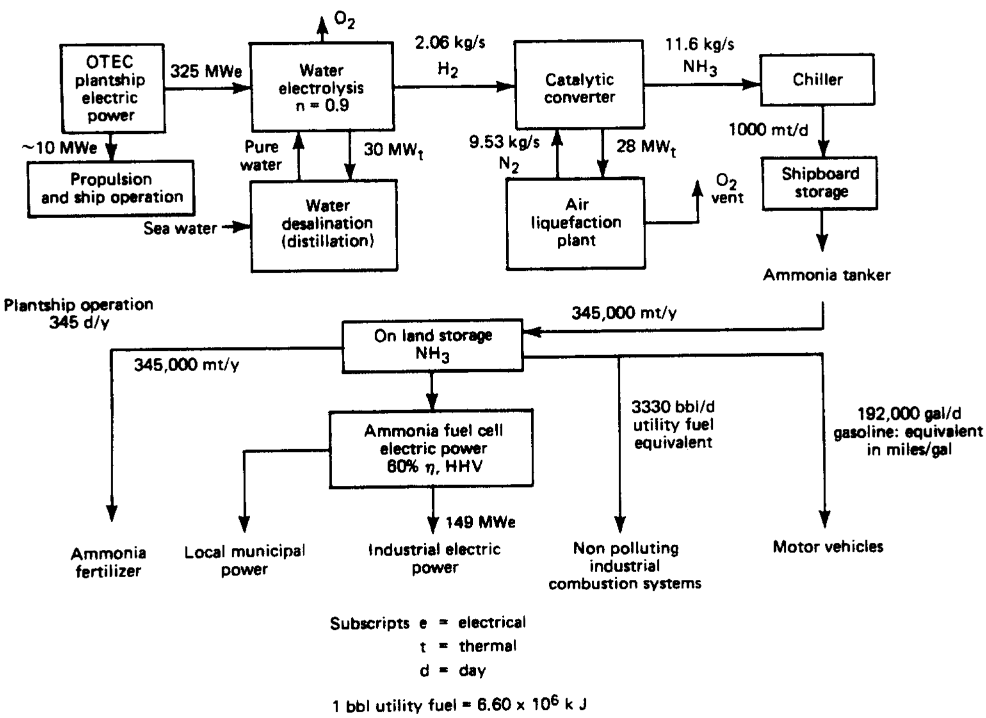

Fig. 3. OTEC ammonia plantship fuel utilization.

Table 2. Estimated cost for OTEC liquid ammonia (1983$)

Plant Investment	40 MWe (nom) demo plant ($M)			8th 325 MWe (nom) commercial plant ($M)		
	Nominal cost	Potential savings (%)	Potential overrun (%)	Nominal cost	Potential savings (%)	Potential overrun (%)
Basic plantship						
Platform system	53.9	13.5	16	159.9	18	18
Hull	25.9	15	20	82.8	20	20
Pumps	11.1	15	15	46.4	20	20
Position control	8.7	10	10	14.1	10	10
Outfitting, furnishings and other	8.3	10	10	16.5	10	10
CWP systems	10.7	25	100	34.9	25	100
Power systems	47.4	24	18	219.4	25	25
Heat exchangers	35.8	28	20	165.5	30	30
Power conversion	8.7	10	10	40.1	10	10
Other	2.9	15	10	13.7	15	15
Deployment services	13.2	32	75	42.4	30	82
Platform (incl NH_3 Plant)	1.5	15	15	4.8	15	15
Power system	1.3	20	40	4.0	15	15
CWP	10.5	35	100	33.6	30	100
Ammonia plant	31.6	23	15	99.9	23	23
Liquid N_2 plant	3.6	10	10	11.6	10	10
Electrolysis plant	13.7	30	35	43.7	30	30
NH_3 synthesis	9.9	20	20	31.8	20	20
Other	4.4	15	15	12.8	15	15
Acceptance, Ind Fac. E&A	7.8	20	20	25.0	20	20
Estimated direct cost	165	21 (av)	29 (av)	581	23 (av)	31 (av)
Interest during construction (14.8% of direct cost)	24.4			86.0		
Total plant investment ($M)	189	149	245	667	513	876
Annual cost ($M)						
Real fixed cost (0.059 × PI)	11.2	8.8	14.5	39.4	30.3	51.7
Annual O&M	1.6	1.5	1.8	10.0	9.4	10.7
Shipping	0.9	0.8	1.0	6.9	6.2	7.6
Total	13.7	11.1	17.3	56.3	45.9	70.0
Annual production (1000 mt)	45.2	45.8	40.7	345	350	335
Ammonia cost ($ t^{-1}) at U.S. Port	303	242	425	163	131	212
Ammonia sales price/($ t^{-1})	509	403	722	259	204	344

METHANOL

Methanol (CH_3OH) is an important industrial chemical principally used now as a feedstock for plastics manufacture. However, in recent years it has emerged as an attractive fuel to substitute for gasoline for motor vehicles. Tests with over 300 General Motors and Ford cars conducted by the Bank of America in California in the period 1980 to 1983, [9], have shown that methanol can be used to replace unleaded gasoline (with only minor modifications in standard automobiles) and at present prices can give a reduced cost per mile driven, as well as lower emissions. Since methanol can be made from coal, as well as natural gas, it offers an important alternative to future dependence on dwindling petroleum resources for vehicle transportation. It is also the preferred fuel for molten-carbonate fuel cells which are expected to become increasingly important for electric power generation.

Methanol is synthesized by catalytically combining 2 mol of H_2 with 1 mol of CO. In present commercial manufacture hydrogen and carbon monoxide are produced by partial oxidation of methane, and the additional hydrogen needed is made by the shift conversion reaction: $CO + H_2O = CO_2 + H_2$. The CO_2 is removed before the hydrogen and carbon monoxide are passed into the catalytic converter. The process uses approximately 1000 m^3 (35 000 ft^3) of natural gas per tonne of methanol produced and approximately the same volume of pure oxygen which is prepared by air liquefaction and distillation.

Rising costs of natural gas in recent years have suggested use of reaction of coal with oxygen, prepared by distillation of liquid air, as a source of the carbon monoxide and reaction of coal with oxygen and water in the shift conversion process to supply the required hydrogen, followed by combination of the gases to form methanol. In the complete process three gram atoms of carbon are theoretically required per gram mol of methanol formed. Thus for a typical coal (Sunnyside, Utah), with a content of 70% by weight of carbon and 4.9% by weight of hydrogen, 1.27–1.6 tonne of coal would be required per tonne of methanol formed, depending on whether the hydrogen in the coal could be used directly in methanol synthesis or would first be oxidized to water. Design estimates quoted for proposed land-based methanol-from-coal plants call for 1.5–2.1 tons of coal to be consumed per ton of methanol output.

The use of OTEC plantships to manufacture methanol is of particular interest because its synthesis requires pure hydrogen and oxygen as feedstocks, both of which would be produced together at low cost by water electrolysis on OTEC ships. Because costs are low for shipment of coal to the ship, and for methanol from the ship to ports in the U.S. ($\sim\$12\,t^{-1}$), economic evaluations indicate that OTEC methanol could be delivered to U.S. ports at lower costs than are projected for new land-based methanol plants of conventional design.

After an initial favorable evaluation of the OTEC methanol concept at APL, a contract was awarded to Brown and Root Development, Inc. (BARDI) to conduct a conceptual design evaluation of an OTEC methanol plantship that would draw on engineering information BARDI had developed for a barge-mounted methanol-from natural gas plant, and would use BARDI operating experience for a gasifier of the Texaco design, which uses a coal slurry as the feed [10]. The APL baseline design of a 40 MWe OTEC ammonia plantship was used to provide design information for the platform, power system and auxiliaries. The BARDI contract led to the design of a 160 MWe methanol plantship with design output of 1000 tonne of methanol per day, and coal slurry input of $750\,t\,d^{-1}$ (coal content). The study confirmed the expectation that the coal requirements would be one-half to one-third that of the projected land plant of the same methanol output [10].

An artist's sketch of the BARDI plant is presented in Fig. 4. The plantship dimensions, $275 \times 102 \times 20$ m, are comparable with those of a 350 000 ton super tanker, $366 \times 72 \times 20$ m.

During the BARDI study it became apparent that

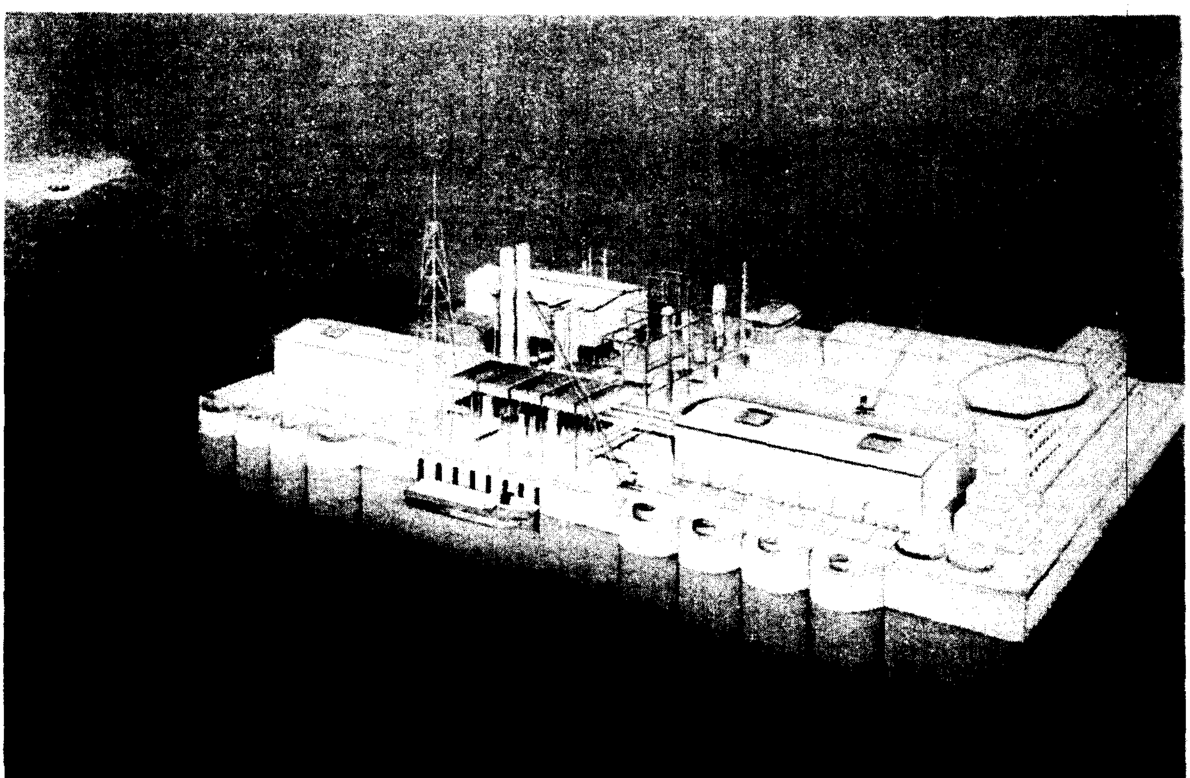

Fig. 4 160 M We (nominal) OTEC methanol plantship $1750\,t\,d^{-1}$.

major improvement in the plantship output would be possible if a new gasifier under development by Rockwell International Corp. [11] was substituted for the state-of-the-art Texaco unit. For this gasifier pulverized dry coal is injected along with steam and oxygen into a cylindrical vessel containing molten sodium carbonate at 1000°C. The ash and sulfur in the coal react with the melt and are retained in solution, and the reaction is very rapid so that the product gases exit at equilibrium as a concentrated mixture of CO and H_2, with minor amounts of CO_2 (6%), CH_4 (2.8%) and H_2O (7%) (by volume).

A design study of the use of this process to replace the Texaco slurry gasifier in the BARDI plantship design has recently been completed in a contract awarded to Ebasco Services, Inc. in cooperation with Rockwell International. The study shows that the output of the nominal 160 MW plantship could be increased to 1750 t d^{-1} by the advanced process without increasing the plantship area. Thus significant reduction in methanol cost would be possible [12].

The increased methanol output requires increase in the coal input to 1363 t d^{-1} of which 120 t d^{-1} is used for supplementary steam production. Thus the ratio of coal input to methanol output for this OTEC methanol process is 0.78 compared with 1.5–2.1 for the land based methanol-from-coal processes.

If major use of methanol as an automobile fuel occurs in the future the saving in coal use of the OTEC methanol process would have important future consequences in reduction of CO_2 additions to the atmosphere, which must ultimately be controlled if the 'greenhouse effect' is to be avoided.

Figure 5 is the schematic diagram of the process, and Table 3 presents the estimated plant investment and methanol cost and sales price.

The cost estimates for the 160 MW (nominal) OTEC power plant and ship systems are derived from the detailed estimates and costs for the 40 MW baseline ammonia plantship design, using scaling and learning factors judged to be appropriate. The Rockwell–Ebasco estimates are used for the gasification and methanol synthesis plant equipment. Installation cost multipliers are based on process unit complexity.

The costs for this plant are based on full-scale costs and operating experience with methanol synthesis plants, and tests at 1 ton/h coal input to the Rockwell gasifier, which provided data on the exhaust gas com-

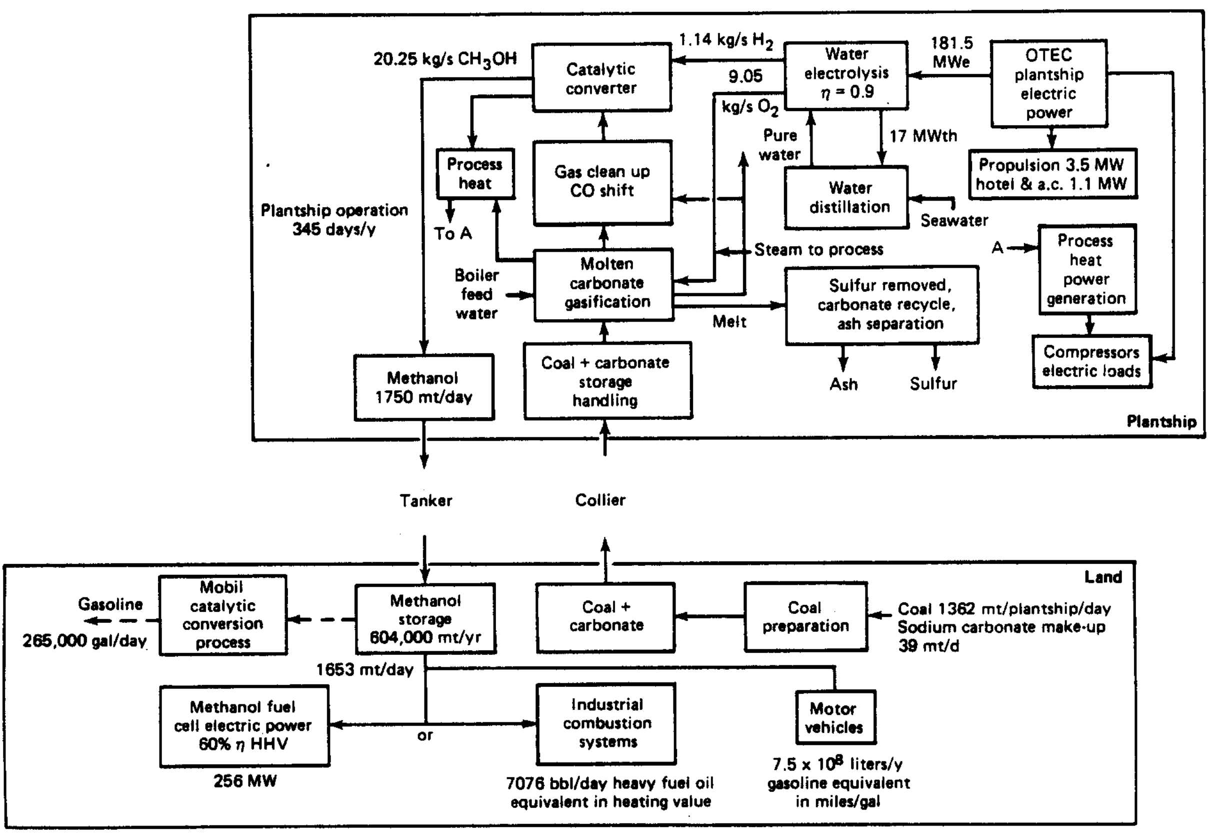

Fig. 5. OTEC methanol plantship 160 M We (nom).

Table 3. Estimated cost of OTEC methanol (1983$)

Plant Investment Basic plantship	160 MWe (nom) ($M) Nominal cost	189 MWe (net) Plantship Potential savings (%)	 Potential overrun (%)
Platform system	161.7	14	16
Hull	81.30	15	20
Pumps & water distribution	39.4	15	15
Position control	18.7	10	10
Outfitting, furnishings, and other	22.3	10	10
CWP systems	29.4	25	100
Power systems	158.4	25	18
Heat exchangers	127.2	28	20
Power conversion	23.4	10	10
Other	7.8	15	15
Deployment services	36.4	30	83
Platform	4.7	15	15
Power systems	3.5	15	15
CWP systems	28.2	35	100
Methanol plant	292.7	15	15
Coal preparation and molten carbonate gasifier	35.9	15	15
Gas clean up and CO shift	62.9	15	15
Acid gas removal and sulfur recovery	17.0	15	15
Methanol synthesis & distribution	52.1	15	15
Steam system	19.4	15	15
Water & waste treatment and carbonate regeneration	20.7	15	15
Service systems	30.0	15	15
Spare parts catalyst fees and Indirects	54.7	15	15
Electrolysis	55.0	30	35
Acceptance, Ind Fac E&A	17.2	20	20
Estimated direct cost	752	19 (av)	24 (av)
Interest during construction (14.8%)	111		
Total plant investment ($M)	863	698	1071
Annual cost ($M)	102	84.7	125.0
Real fixed cost (0.059 × PI)	50.9	41.2	65.8
Operating cost			
Crew & mgrs	9.1	7.7	10.5
Catalyst & materials	7.0	6.0	8.1
Coal $50 t^{-1}	23.3	19.8	27.0
Coal shipping $11 t^{-1}	5.2	4.4	6.0
Methanol shipping $11 t^{-1}	6.6	5.6	7.6
Annual production (liters)	7.48×10^8	7.59×10^8	7.16×10^8
Methanol cost $$1^{-1}$ at U.S. port	0.136	0.112	0.174
Methanol sales price $$1^{-1}$ at U.S. port (0.1085 × PI)	0.194	0.157	0.244
Equivalent price, high-octane unleaded $$1^{-1}$)	0.259	0.209	0.326

position. Thus the process requirements, plant layout and estimated costs are believed to be realistic.

Methanol production capacity at present greatly exceeds demands due to overbuilding before the recent recession. As a result the market price ($0.45 gal^{-1} at Gulf Coast plants, January 1984) is well below the cost of production from new plants, which is estimated to be in the range of $0.55–0.66 gal^{-1} (1983$). With projected near term increases in demand, retirement of old plants and expiration of low cost gas contracts it appears that

OTEC methanol would provide attractive returns to investors as soon as the first commercial plantships could be brought into operation after 1990.

CONCLUSION

OTEC plantships designed for operation at sites throughout the tropical oceans are a potential source of hydrogen, ammonia and methanol in amounts that could significantly reduce U.S. and world dependence on fossil fuels. Engineering design studies and financial analyses indicate that costs of these OTEC products at U.S. ports would be competitive with projections of their costs if produced by alternative methods on land, and the OTEC process would have significant economic, environmental and ecological benefits. Implementation of the full OTEC potential would also bring imponderable gains in national and international security.

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