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**STUDY OF INTEGRATION ISSUES TO REALIZE THE MARKET
POTENTIAL OF OTEC ENERGY IN THE ALUMINUM INDUSTRY**

Final Report

By

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MASTER

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**Reynolds Metals Company
Sheffield, Alabama**

and

**TRW, Incorporated
Redondo Beach, California**

U.S. Department of Energy

Solar Energy

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1.0 INTRODUCTION AND SUMMARY

The goal of the present study is to examine the various integration issues which must be considered to realize the market potential for the use of Ocean Thermal Energy Conversion (OTEC) energy by the aluminum industry. Several previous studies⁽¹⁻³⁾ have identified aluminum as an energy-intensive product with the potential for being produced using OTEC-derived energy on or near OTEC power plants. We have considered the technical integration problems and economic potential in greater detail and have identified the chloride reduction process as an attractive candidate for use with OTEC power-systems.

The American aluminum industry now uses about 4% of all electrical power produced in the United States. The market for aluminum is growing at about an annual rate of 7% per year, with many new applications being expected in the transportation industry where the light weight of aluminum can lead to fuel economies which are reflected in conservation of scarce petroleum resources. The development of environmentally acceptable energy sources adequate to power the projected expansion in aluminum capacity over the next few decades is a formidable problem. There are two approaches being followed. One is to find new power sources such as OTEC, and the other is to improve the process so that less energy is required to produce aluminum metal. The aluminum industry is investigating both courses of action.

1.1 OTEC Background

The OTEC concept—an ocean thermal energy conversion (OTEC) power plant uses the temperature difference (ΔT) between warm surface water and cold deep water to drive a heat engine. In the closed Rankine cycle OTEC system conceived by d'Arsonval in 1881,⁽⁴⁾ a working fluid (e.g., ammonia) vaporized by heat exchange with warm water, drives a turbine generator, and is condensed by heat exchange with cold water drawn from a 700-1200m (2300-3900 ft.) depth (Figure 1-1). A summary of recent closed cycle OTEC system studies is given in Reference 5.

In 1930, Claude demonstrated an open Rankine cycle process at Mantanzas Bay, Cuba.⁽⁶⁾ Warm water was flash-vaporized at low pressure to drive a turbine and then was condensed by direct contact with cold water from 700 m depth (2300 ft) by a 1.6 m (5.2 ft.) diameter, 1737 m (5700 ft.) long, cold-water pipe (CWP). From a ΔT of 25.2°F (14°C) his undersized turbine generated 22 kWe. In 1956 a French team designed a 3.5 MWe (net) open cycle plant for installation off Abidjan on the Ivory Coast of Africa and demonstrated the necessary CWP deployment. The project was marginal economically and was dropped when a hydroelectric plant was installed nearby. Two problems with the open cycle are the size of turbines required because of the low steam pressure and the development work needed on the direct-contact condensers.

More recently, OTEC open cycle innovations, such as the mist cycle, have been investigated. However, both the conventional open cycle and the new innovations will require significant research and development. Therefore, a

FIGURE 1-1. SIMPLIFIED LOOP DIAGRAM FOR THE CLOSED RANKINE CYCLE OTEC SYSTEM

FIGURE 1-2. TEMPERATURE-DEPTH VARIATIONS FOR THREE SITES

conventional closed cycle OTEC power plant is the basis for the current study. An overview of the various "advanced" OTEC concepts can be found in the proceedings from the 6th OTEC Conference.⁽⁷⁾

The OTEC Resource-ocean covers 71% of the Earth's surface and receives the majority of the solar energy incident upon Earth. In semitropical and tropical oceans, the available ΔT is sufficient for economical OTEC operation and is available 24 hours a day. The vast potential for OTEC implementation can be appreciated by noting that a quantity of electric power equal to the entire projected U.S. demand in the year 2000 (about 7×10^5 MWe) could be obtained by extracting from the oceans in the $\pm 10^\circ$ latitude band near the equator an amount of energy equal to only 0.004% of the incident solar energy.

Figure 1-2 shows typical temperature versus depth profiles off Keahole Point, Hawaii; off Punta Tuna, Puerto Rico; and for a grazing pattern in an area in the South Atlantic Ocean 300 to 900 nautical miles east of Recife, Brazil (designated ATL-1).⁽³⁾ Table 1-1 presents seasonal variations in ΔT for the same three sites plus one 25 nautical miles east of Miami, Florida; one in the Gulf of Mexico 150 nautical miles WSW of Tampa, Florida; and for a grazing pattern in an area in the North Pacific Ocean 200 to 400 nautical miles SW of Acapulco, Mexico (designated PAC-2). The Puerto Rico and Hawaii sites are of interest in the U. S. OTEC program because of the needs of these islands for an alternative to imported fossil fuels (potential nuclear power plant sites are limited) and the possibility that one of them will be chosen for an early demonstration of the "island industry" OTEC option. The grazing plants in ATL-1 and PAC -2 would seek out the highest ΔT 's based on historical plots of monthly surface temperature contours plus daily information from satellites which would indicate the path to take to optimize power output.

Historical data on world-wide thermal resources were collected, smoothed, and presented by W. A. Wolff and associates at the above referenced 6th OTEC Conference. Figures 1-3 and 1-4 are from the proceedings⁽⁸⁾ and indicate the large scale distribution of ΔT and location of some candidate OTEC sites. Charts of the large scale distribution of ΔT have been printed and distributed by the DOE. These charts are useful for an initial assessment of the resource. As will be discussed later, the plant output is sensitive to seasonal variation of ΔT . Therefore, seasonal characteristics as well as bathymetry, weather, sea-state and current statistics must be included in the resource assessment.

Previous studies had pointed out that Hall-type reduction cells, if placed onboard on OTEC plant, would have to be stabilized against platform motion, and that this would add cost, if it could be done at all.^(1, 2) They also noted that this problem apparently could be alleviated with the Alcoa chloride process cells.⁽¹⁾ Our investigation has included drained-cathode Hall cells, which would alleviate this problem, and two alternative chloride reduction processes.

We may note that most of the early OTEC economic studies were based on the concept of a "levelized busbar" cost of electricity, which is a concept used

FIGURE 1-3. LARGE-SCALE DISTRIBUTION OF OTEC THERMAL RESOURCE BASED ON ΔT ($^{\circ}\text{C}$) BETWEEN SURFACE AND 1000-M DEPTH (ANNUAL AVERAGE)

FIGURE 1-4. LOCATION OF THE TEN MOST RECENTLY INVESTIGATED SITES

TABLE 1-1. MONTHLY VALUES OF ΔT FOR SELECTED SITES

	<u>Miami</u>	<u>Tampa</u>	<u>ATL-1</u>	<u>PAC-2</u>	<u>Puerto Rico</u>	<u>Hawaii</u>
	ΔT	ΔT	ΔT	ΔT	ΔT	ΔT
Mo.	$^{\circ}\text{C}$	$^{\circ}\text{C}$	$^{\circ}\text{C}$	$^{\circ}\text{C}$	$^{\circ}\text{C}$	$^{\circ}\text{C}$
Jan	19.1	19.7	23.5	22.6	21.3	20.6
Feb	19.5	20.6	24.3	22.9	20.9	20.1
Mar	19.7	20.6	25.2	23.6	20.9	20.0
Apr	19.8	20.9	25.2	25.1	21.2	20.6
May	20.4	23.0	24.2	25.1	22.2	21.3
Jun	21.3	24.3	24.4	24.5	22.6	21.3
Jul	22.8	24.6	23.6	24.1	23.0	22.4
Aug	22.8	25.0	24.3	23.9	23.0	22.7
Sep	23.0	24.2	22.4	23.8	23.6	22.7
Oct	22.3	23.0	23.3	23.6	23.9	22.5
Nov	20.8	21.8	22.6	24.1	23.3	21.5
Dec	20.0	21.1	23.3	23.2	22.3	20.7
Avg	21.0	22.4	23.9	23.9	22.3	21.4

ΔT between surface and 900-m depth for ATL-1 and PAC-2;
1000 m for Tampa, Hawaii and Puerto Rico; 700 for Miami.

Data for ATL-1 (east of Recife, Brazil) and PAC-2 (SW of
Acapulco, Mexico) are for a grazing concept.

by the electric utility industry to evaluate capacity expansion opportunities. We have based our economic evaluations on return on investment or return on assets using a discounted cash flow analysis. These evaluations are based on the assumption that there will be mature industries providing OTEC power systems and that the required new aluminum reduction technologies will also have been demonstrated on a commercial scale, so that research and development costs will not have to be considered in the economic analysis to determine the return on investment.

1.2 Aluminum Industry Background

The analysis covers two processes for producing aluminum from its ores: the conventional Bayer-Hall process whereby the alumina (Al_2O_3) values are extracted from bauxite by the Bayer process, and the alumina is then electrolytically reduced in the presence of carbon to produce aluminum metal; and the chloride process where either bauxite or clay is reacted with chlorine in the presence of carbon to produce aluminum trichloride (AlCl_3) which is then electrolytically reduced to produce aluminum metal, and chlorine which is recycled. Other routes for production of aluminum metal from its ores have been suggested, but none of these has been demonstrated at a scale such that its use in an OTEC scenario could be projected with any faith in the economics.

The present domestic capacity for production of aluminum is about 4,800,000 MT/yr. Figure 1-5 shows the locations of alumina plants and aluminum smelters in the United States. The Aluminum Association predicts a continuation of the recent historical growth rates in excess of 7%. Continuation of this rate growth would require an additional 10,000,000 MT of capacity in 9 years. The electrical energy required to convert 1.93 kg of alumina (Al_2O_3) to 1 kg of aluminum metal using presently available technology is 13.67 kWh. Between 1000 MW and 2000 MW of new electrical generation capacity per year will be needed if this growth rate is to be maintained. OTEC energy could provide some of this additional capacity.

The production of aluminum from bauxite, its primary ore, involves several energy-intensive steps. Most of the world's aluminum metal is produced by a combination of the Bayer process and the Hall process as shown in Figure 1-6, although there are other processes being actively investigated. In the Bayer process, alumina (Al_2O_3) is chemically separated from bauxite, which is generally a mixture of aluminum, silicon, iron, and titanium oxides. In the Hall process the alumina is dissolved in cryolite, then electrolytically reduced in the presence of carbon to form aluminum metal and carbon oxides, which are vented to the atmosphere.

Traditionally in the United States, the Bayer process is carried out in regions close to the bauxite supply where low cost thermal energy (natural gas) is available, and most of the alumina is shipped to regions with low cost electrical energy (hydroelectric) where the Hall process is carried out. The electrical energy requirements of the reduction process suggest that it may be a candidate for OTEC commercialization.

FIGURE 1-5. LOCATION OF ALUMINA PLANTS AND ALUMINUM SMELTERS IN THE UNITED STATES

FIGURE 1-6. FLOW CHART OF ENERGY CONSUMPTION IN ALUMINUM PRODUCTION

There are two potential ways in which OTEC energy can be used by the aluminum industry to power a reduction plant. The first is to have the OTEC power plant on shore or moored at sea just off the coast in deep water, sending the energy to a reduction at or near the shore line (Figure 1-7). The second method is to put the reduction plant on a floating platform integrated with the OTEC power plant, and operate at sea in those regions with high ΔT (Figure 1-8).

The floating OTEC/aluminum plant has the greatest potential for achieving the lowest energy costs inasmuch as the capital cost of the OTEC power plant varies at $(\Delta T)^{-1.8}$ as we will see in Section 3.0. Therefore, locating the OTEC/aluminum plants in those areas of the ocean which have the highest temperature differential should lead to the lowest energy costs. Such plants have been described in OTEC literature as "grazing" plants and preferred sites in the equatorial Atlantic and Pacific regions have been identified. In terms of the aluminum industry, the thermal resource available in these equatorial regions is very large. There are roughly 50 million square miles ($120 \times 10^6 \text{ km}^2$) of ocean surface where the depth is greater than 1000 m and where the temperature difference between the surface and the 1000 m depth is greater than 20°C .

For the floating OTEC/aluminum plantship, it is anticipated that low capital cost standby generation capacity, presumably gas-turbine-powered, would be provided to allow the reduction plant to be shut down in an orderly fashion in case of a forced outage of the OTEC power system, or for use in the event of the occurrence of natural phenomena such as a storm which might reduce the OTEC generation capability. Since the reduction plant operates continuously for 365 days per year, with a load factor which approaches unity, spare OTEC generating capacity must be provided to insure that nameplate electrical capacity is available at all times, such as when the OTEC electrical generation equipment is down for routine repairs or maintenance or when heat transfer surfaces are being cleaned, etc. While it may be possible to have a short-term (hour or so) turndown of the power to the OTEC reduction plant, economics and the physical processes favor high utilization of the capital intensive facilities.

1.3 Candidate Reduction Processes and System Configurations

The aluminum smelting industry is presently based on the reduction of alumina to aluminum metal using the Hall/Heroult electrolysis process. The Hall cell, shown in cross-section in Figure 1-9, consists of a carbon-lined cathode and a consumable carbon anode. Alumina dissolved in cryolite is placed in the cavity formed by the cathode and electric current is passed from the cathode to the anode, producing carbon oxide gases at the anode surface which bubble off. The aluminum metal is deposited on the cathode and forms a pool of metal (called a pad) on the cathode where it collects until it is periodically removed.

Unfortunately, as discussed in Section 3.2, the Hall cells are susceptible to having the molten metal form an electrical short between the cathode and anode if the cell moves, so that it is not feasible to use them on a floating plantship. Two alternatives do appear to be feasible: 1) Hall cells with drained cathodes, and 2) the aluminum chloride smelting process.

FIGURE 1-7. OTEC/ALUMINUM SHORE BASED PRODUCTION MODEL

FIGURE 1-8. OTEC/ALUMINUM FLOATING PLANTSHIP SUPPORTED BY SHORE-BASED BAYER PROCESS PLANT

FIGURE 1-9. ALUMINUM REDUCTION CELL

Fig. 1-10 TYPICAL DRAINED-CATHODE HALL CELL WITH PREBAKED ANODES

In the drained-cathode Hall cell, which has previously been described in the patent literature, a special cathodic material wettable by molten aluminum covers the carbon-lined bottom of the cell. Figure 1-10 shows a cross section of the drained cathode Hall cell. This means that a metal pad is not required, so that the molten metal can be drained from the area between the electrodes as it is produced. As a result, the cell should be much less susceptible to shorting as a result of motion, either horizontally or vertically, as discussed in Section 2.3.

In the aluminum chloride smelting process, alumina is converted to aluminum trichloride by reacting Al_2O_3 with Cl_2 in the presence of carbon, releasing carbon oxides. A bipolar reduction cell is used to reduce the aluminum trichloride to chlorine gas and molten aluminum as discussed in Section 2.4. Figure 1-11 shows a cross section of the bipolar aluminum chloride reduction plant.

Four potential system configurations are:

- A. and B. The Hall process configurations previously shown in Figures 1-7 and 1-8.
- C. Shore-based chlorination plant producing aluminum trichloride (AlCl_3) from bauxite or kaolin clays, the AlCl_3 being reduced on the OTEC platform to produce aluminum metal and chlorine. The chlorine is recycled to the chlorination plant. This configuration is shown in Figure 1-12 as Option I.
- D. Plantship chlorination of calcined bauxite or kaolin clays to produce AlCl_3 and the reduction of the AlCl_3 on the OTEC platform to produce aluminum metal. This configuration is shown in Figure 1-13 as Option II.

1.4 Economic Analysis and Integration Issues

The methodology has been to develop physical model which describe the characteristics of the production process as a function of the several available variables and establish the physical sizes of the various components which allows a cost estimate to be developed. The resulting cost models are used to determine the rate of return using discounted cash flow techniques.

The investors place a certain amount (their equity) at risk to get a project started. The additional funds required are borrowed, and the profits from the project are then used to pay off the loan and to reward the original investors. Since the investment banking community normally uses the discounted cash flow concept, we have adopted their method of financial analysis.

The major institutional issues examined are the tax and financial policies, i.e., depreciation, investment tax credits, and loan guarantees, since they figure strongly in the cash flow. With respect to risk, it is not so much a question of physical risk of the OTEC plantship foundering during a storm, this can be covered by insurance which has been factored into the economic analysis, but whether the plant will be constructed within the projected

Fig. 1-11. Cross Section of Bipolar Reduction Cell for AlCl_3

Fig. 1-12. OTEC/ALUMINUM CHLORIDE PROCESS - OPTION I, CHLORINATION ON SHORE

FIG. 1-13. OTEC/ALUMINUM CHLORIDE PROCESS - OPTION II
CHLORINATION ON PLANTSHIP

budget and will attain the predicted levels of performance and system reliability. The largest single factor in reducing the perceived risk will be the demonstration of long-term operational reliability by an OTEC power plant operating at sea. Until such long-term operational data are available, notwithstanding the more favorable returns on investment from OTEC plantship options, the aluminum industry will quite probably be interested only in those OTEC applications where the production facilities are located on shore and the OTEC energy is delivered by cable with alternative electrical power being available from a local utility grid or standby power system.

The basic methodology has been to use the case method where we assume various locations for the OTEC/aluminum installation and then investigate the return on investment which could be realized through the use of OTEC power systems. The several process options are examined and their rates of return are projected under various tax and financing options. These candidate applications are then compared with a baseline case, which we have selected as a new conventional Bayer-Hall process complex constructed on the U. S. Gulf Coast.

From these results it is hoped that others can draw some conclusions as to what technological advancements and changes in institutional factor such as tax laws can do to make OTEC/aluminum commercialization a reality.

1.5 Specific Economic Model Approaches

Due to the sensitivity of the cost of producing aluminum to the cost of electricity, it did not appear at the start of the program that OTEC-derived electricity, assumed available along the U. S. Gulf Coast in at rates of \$0.065 to \$0.105/kWhr (in 1978 dollars) would a priori be economically competitive with hydroelectric power available in several areas throughout the world during that period. For this reason, our primary efforts were focused

on the potential placement of the reduction plant aboard the OTEC platform as in Figure 1-8, since the OTEC energy would be delivered to the process with the highest efficiency. Furthermore, this approach may allow the onboard processing facilities to be included under any loan guarantee benefits, or solar energy investment tax credits which might be applied to OTEC projects.

We have used the established world price of aluminum ingot, assumed to increase in price at the same rate as the general inflation rate, to predict the potential income from OTEC/aluminum projects. This price in the past has correlated well with the U. S. Wholesale Price Index and, therefore, the relationship between the selling price for any aluminum produced and the costs of producing it can be predicted. However, on the cost side there is really no "free market" for alumina, a major input to the Hall process. Because of the uncertainties in the "price" of alumina, i.e., how much profit or taxes are included in the price, etc., it was deemed appropriate to include the Bayer process facilities in the economic model. Another important reason for doing this is that the decision for a substantial increase in metal production has with it the implicit decision that alumina production has to be increased somewhere by a corresponding amount. It therefore appeared that a more consistent treatment would be obtained if we considered a complete project which included a Bayer plant, a Hall plant, the OTEC power systems, and the necessary infrastructure as part of the decision package.

Even though we concluded that the conventional Hall cell reduction plant could not operate in a marine environment where there was any periodic platform movement, we retained it as a reference economic model because it is so well known by the industry. Drained-cathode Hall cells can be made more motion tolerant and can be operated more efficiently than the conventional Hall cells but still require a large deck area when on an OTEC plant-ship.

The aluminum chloride reduction process has several advantages for the OTEC application. The cell configuration is such that it should be insensitive to motion; since bipolar plates in multiple cell stack assemblies can be used, only a small amount of deck area may be required; and the cell should be easier to start up and shut down. In addition, the cell is more efficient in the use of energy. An aluminum chloride reduction process pilot plant has been operated at the 33,000 ton/year level. The major uncertainties are the economic viability of a plant producing aluminum trichloride from bauxite or other alumina-rich materials such as kaolin clays, and the problems of transporting the aluminum chloride from the shore to the floating plantship and returning the chlorine to shore.

With regard to scale of the project, we have considered two basic approaches: a) an integrated production chain using five 100-MWe OTEC/aluminum plantships with a combined annual output of about 360,000 MT of ingot (this output is based on a Bayer plant with an annual output of 700,000 MT of alumina), and b) use of optimum-sized OTEC plantships (about 400 MWe) with the production chain adjusted to support two such plantships. Because of the advantages of scale in capital cost, the latter model yields better rates of return. Both approaches require large capital investments.

The basic assumptions used in the economic analysis were that 87-1/2% of the floating plant and asset could be covered by Maritime Administration (MarAd) loan guarantee, and that the shore-based parts of the project could have a 70/30 debt to equity ratio. It was assumed that the long-term interest rates would be 12%, short-term interest rates 10%, and that the portion of the debt covered by the MarAd guarantee would have an interest rate of 11%. The corporate income tax rate was assumed to be 46%. In addition to considering the standard 10% investment tax credit (ITC), cases were considered where the special additional 15% solar energy ITC was applied to the OTEC plantship and the onboard equipment. To fully utilize the available ITC, it was necessary to assume "project" financing where there were a number of industrial partners with income tax liabilities which could be used to offset the ITC. We assumed 11-year depreciation schedule and 7% imbedded inflation rate or GNP deflator at which the cost of raw materials, labor, etc., as well as the sales price of the products would increase. For some tests of the Bayer-Hall complex on shore, the electricity costs were assumed to escalate at rates faster than the GNP deflator.

1.6 Results

Our economic analysis indicate that a new Bayer-Hall complex constructed on the U. S. Gulf Coast and paying \$0.0235/kWh for electricity would break even (no net return). A competing 500-MWe OTEC platform moored in the Gulf of Mexico where the ΔT is 21.3°C, sending the power to shore through a 100-mile cable, with the OTEC power system supplying 90% of the electrical power required by the Bayer-Hall plant and the remainder being purchased from the utility grid at the prices expected during the life of the project, could, under favorable ITC conditions (including the aforementioned solar energy ITC for the OTEC plant), and for the project financed with a MARAD loan guarantee for the OTEC system, would return 7.8% on investment after taxes if there were sufficient other income tax liabilities so that the ITC could be used in the first year of production.

This return is far below the 12% "threshold" for capital investment projects being sought by some members of the aluminum industry.

Because of the small ΔT available along the Gulf Coast and the large distance from the shore (80-150 nautical miles) needed to obtain it, it is doubted that an OTEC power system, or any other power system as a matter of fact, could ever have a low enough cost of energy to make a "green field" Bayer plant and Hall plant along the U. S. Gulf Coast competitive when compared to hydroelectric power options now available to the industry. Sites with higher ΔT 's in deep water immediately off the coast line, and potentially more favorable tax structures are favorable factors in the OTEC context. The U. S. Virgin Islands, Guam, Puerto Rico, and Mindanao in the Philippine Islands were considered as candidate locations, and the highest rate of return, 12.4%, was projected for Mindanao. A plant in the Virgin Islands would return about 8%, but Guam and Puerto Rico would yield only about 5.5% rates of return under the assumed conditions because of the higher projected overseas construction costs.

The drained-cathode Hall cell plantship was investigated for low anode current density, which yields better efficiency, but more cells (higher cost

and more platform space), and for high current densities (lower cost and space need in spite of the lower efficiency). The highest rate of return on investment, 7.7%, is projected for the high (14kA/m^2) current density case operating off Guam with a ΔT of 24°C .

For the chloride reduction process, it was assumed that a slight modification of the Toth process would be used for producing the aluminum chloride from kaolin clays, the chlorine being recycled from the OTEC/aluminum plantship to the Toth process plant on shore. Analysis of the aluminum chloride process is subject to the largest error because the Toth Chlorination process has not been demonstrated at anything near commercial scale, nor have the problems of transporting the AlCl_3 to the plantship in a commercial scale been addressed. While the return of the chlorine to the shore base is less of a technical problem, there is a large uncertainty in both the capital costs and the operating and maintenance costs in this approach. It was assumed as a base case that the chloride reduction plantships would be located about 125 miles from shore in the Gulf of Mexico, so that the plantship could be served on a 24-hour round trip cycle by support vessels. By having a 7-day supply of reactants on the plantship, five or six plantships could be serviced by two support vessels.

For this case the rates of return become interesting due to many favorable factors: (1) lower cost of the raw materials (green versus calcined coke; kaolin versus bauxite, etc.), (2) the availability of additional salable by-products such as rutile and hematite, (3) lower plant cost because of the compact nature of the bipolar reduction cells, and (4) reduced OTEC capital cost due to the higher cell efficiency. The projected return on investment is 17.9% after taxes for two 400-MWe plantships or 17.0% for five 100-MWe plantships in the Gulf of Mexico. Moving the five OTEC plantships and shore-support base to Mindanao where the ΔT is 24°C projects a potential return of 13.7%. For the five plantships and their support base at Puerto Rico or the U. S. Virgin Islands, the projected returns are 13.1%, and 13.7%, respectively.

If we consider the option where the aluminum chloride production and reduction facilities are located on a tropical island which has a steep underwater slope (so that the cable runs are minimal) with an average ΔT availability of 24°C , it is possible to eliminate the costs of equipment and the labor required for storing and moving the AlCl_3 , the aluminum metal, and the Cl_2 . Also eliminated are other costs such as the onboard standby power system, etc. This option results in projected rates of return up to 18.4%.

Once again, we must caution that there is a great uncertainty in these results because we are considering a metallurgical/chemical technology which has not been demonstrated on a commercial scale, and a power system which is even less well-defined in terms of demonstrated capability over extended periods of time.

We believe that avoidance of risk will play a prominent role in selecting the order in which the various OTEC/aluminum options are brought into commercial practice. Another factor will be the ability of the aluminum industry to raise cash for financing the multibillion dollar projects which

are required. It appears inescapable that the aluminum industry will have to raise the funds for the aluminum production facilities, by some means. With existing debt-to-equity ratios higher than overall industry averages, the aluminum industry will tend to favor those power generation options which allow others to raise the capital for either conventional or OTEC power systems. This would tend to favor those OTEC options where the power is delivered to the shore-based plant by a cable, so that there can be a clean line of demarcation of ownership, which will facilitate approaches such as leveraged leasing.

Because of these two factors, the following is a possible sequence in which the various OTEC/aluminum options will be brought to commercialization:

1. Hall process reduction plants on selected Pacific Islands with 24°C ΔT and underwater topography favorable for short distance OTEC power transmission or shore-based OTEC plants.
2. Aluminum chloride production plants on such islands with short-distance OTEC power transmission or shore-based OTEC plants.
3. Aluminum chloride production plants in the Gulf of Mexico or Caribbean or Pacific islands with floating OTEC/chloride reduction plantships offshore.

We see three main barriers to the widespread application of OTEC by the aluminum industry in the near time frame:

1. The present availability of inexpensive hydroelectric power in many parts of the world;
2. The lack of an operating OTEC power system at the 100 MWe scale demonstrating the costs and the reliability of OTEC power systems; and
3. The present U. S. tax policies which mitigate against the formation or retention of capital in the amounts required for an OTEC/aluminum production project.

It is anticipated that with the passage of time the first barrier will eventually disappear, and that by an aggressive OTEC plant demonstration program, as spelled out in PL 96-310, the second barrier will be removed. It is anticipated that during this period the aluminum industry will in its own self-interest continue development of the process technology which could also be used on an OTEC aluminum plantship with minimum modification. Thus, given a reasonable period of time, the technical and economic factors which would make the utilization of OTEC systems in the best interest of the aluminum industry may occur, and if the necessary capital can be raised, OTEC-derived aluminum will become a reality.

2.0 OTEC SYSTEM AND PLANTSHIP CHARACTERISTICS

2.1 The OTEC Power System

The U.S. Department of Energy (DOE) has sponsored several power system development studies which have resulted in preliminary designs of 10 MWe power modules (PSD-I and PSD-II). These designs (by Westinghouse, Lockheed, G.E., and TRW) differ primarily by the type of heat exchangers selected, materials of construction, and the plant arrangements. The TRW PSD-I design^(9,10) is basis for the current study, i.e., the various arrangement studies and analysis have used this design as a baseline. This is acceptable since the performance and overall cost of the various concepts are very close. The design has been described in detail in reports available from the DOE, only a brief overview is presented here. A general review of OTEC power system design philosophy is given by Dugger, Naef, and Snyder.⁽⁵⁾

A perspective of the 10 MWe power module is shown in Figure 2-1. It shows the arrangement of the main components including externally mounted heat exchangers, the tube cleaning machine on top of the heat exchangers, the turbine/generator and ammonia piping and pumps. The arrangement is compact, yet provides for space and access for maintenance and repair. Both the evaporator and the condenser are of the vertical fluted tube, falling film type, with the seawater inside the tubes.

Ammonia is the selected working fluid since it leads to more compact and less expensive equipment than other fluids. These heat exchangers are approximately 30 feet O.D. by 30 feet long (tubesheet-to-tubesheet).

TRW selected titanium as the tube material based on its expected long life in a seawater environment. This was a minimum risk approach.

The design includes a unique open top which simplifies the water box construction, reduces cost, and allows access to the waterside of the tubes for non-interruptive tube cleaning and repair. Incorporation of existing tube cleaning technology by designing a multiple spindle axial drive with brushes and using a low dosage rate of chlorination is expected to result in effective fouling control.

An open trough cold and warm water distribution system avoids the water hammer effects inherent in closed systems, and eliminate the requirements for expensive water side valves and piping. These open water troughs, coupled with vertical orientation of the heat exchangers, result in a compact power plant configuration with shirt-sleeve environment for maintenance operations on the power module components.

In the arrangement shown in Figure 2-1, the heat exchangers are mounted externally to a barge-type platform. Arrangements with the heat exchangers mounted internally have also been developed. The external mounting saves containment hull space at the expense of a more severe environment compared to internal mounting.

In the semi-submersible plantship concepts discussed later, the power plant arrangement was modified slightly without changing the key design characteristics.

FIGURE 2-1. 10 MWe POWER SYSTEM MODULE

Based on a study by Elliott Company, a four stage double flow axial machine was selected. The turbine efficiency calculated for this design is nearly 90 percent. The proposed control system includes variable nozzles (variable stator vanes) for the first stage. This provides for increased power developed at off-design conditions compared to fixed nozzles.

The ammonia subsystem provides three functions: storage, conditioning, and recovery. A unique feature of this subsystem is that warm seawater is used in the rectification column reboiler which recovers dry ammonia from the wet heel.

The functional characteristics of the design are shown in the process flow diagram, Figure 2-2. Figure 2-3 shows an electrical single line diagram. The integration of the standby turbines will be discussed later. The power budget and other power system parameters are summarized in Table 2-1. Note that these data are for nominal operating conditions of overall $\Delta T = 40^{\circ}\text{F}$ (22.2°C). Performance and cost dependence on actual and design ΔT is discussed below.

The thermal efficiency of an OTEC plant is low, typically between 2 and 2.5 percent, versus conventional power plants with thermal efficiency in the 30 to 40 percent range. However, since the "fuel" is free (except for parasitic pumping power), the thermal efficiency is not a good measure of plant performance. A better measure is what may be called "power efficiency" defined as the ratio of net power to gross power. This ratio is approximately 70 percent for the TRW PSD-I design at the design ΔT of 40°F . As the available ΔT decreases the power efficiency decreases and at a ΔT of approximately 25°F (13.9°C) the plant would yield no net power, i.e., the gross power equals parasitic pumping power.

For the PSD-I design, the net power is essentially linear in the available overall ΔT . For a nominal 10MWe net module (at design $\Delta T = 40^{\circ}\text{F}$) detailed analysis shows that to a very good approximation the net power is given by

$$P_{\text{net}}(\text{MWe}) = 10.00 + 0.694 (\Delta T(^{\circ}\text{F}) - 40) \quad (2-1)$$

as discussed in TRW's preliminary design report¹². An approximate analysis assuming that efficiencies of rotating machinery (pumps and turbines) and heat exchangers are constant independent of ΔT leads to the following model:

$$P_{\text{net}} = P_{\text{Gross Design}} \left(\frac{\Delta T}{\Delta T_{\text{Design}}} \right)^2 - P_{\text{Parasitic Design Losses, Design}} \quad (2-2)$$

The square power reflects the fact that for the ideal cycle the gross power is proportional to cycle efficiency times working fluid flow rate, and both are essentially proportional to ΔT . Equations 2-1 and 2-2 are shown graphically in Figure 2-4. In the range of interest, the approximation Equation 2-2 is close to the result of the detailed analysis.

FIGURE 2-2. PROCESS FLOW DIAGRAM FOR TRW PSD-I POWER MODULE, NOMINAL FLOW CONDITION

1. CY NOTION FOR GROUPS FAULT AND OFFICIALS
SPECIFIED TO BE SPECIFIED BY THAT OFFICIALS
HOLDING OFFICIALS
2. FOR OFFICIALS, GROUPS OFFICIALS OFFICIALS
SEE OFFICIALS SPECIFICATION NO. CP-5516-04
3. FORMS OF OFFICIALS (OFFICIALS) TO OFFICIALS THE OFFICIALS
OFFICIALS OF OFFICIALS NO. 1, NO. 2, AND NO. 3.

FIGURE 2-3. ELECTRICAL SINGLE LINE DIAGRAM FOR TRW PSD-I POWER MODULE

TABLE 2-1. 10 MWe POWER MODULE CHARACTERISTICS (NOMINAL)

WATER (HYDRAULIC) SUBSYSTEM	WARM	COLD
TEMPERATURE, °F	80	40
VOLUMETRIC FLOW RATE, GPM	934,700	494,300
MASS FLOW RATE, LB/SEC	75,970	70,500
PIPE SIZE (ID-BASED ON 6FPS), FT	15.9	15.3
TOTAL PRESSURE DROP, FT	10.6	13.0
PUMPING POWER, MWe	1.35	1.78
SHAFT HORSEPOWER, BHP	1680	2210
ASSUMPTIONS:		
MOTOR/GEAR EFF. 92.4%		
PUMP EFF. 87%		

AMMONIA CYCLE

AMMONIA VAPOR FLOW RATE, LB/SEC	807.2
AMMONIA VOLUMETRIC FLOW RATES	
TURBINE INLET, ACFS	1867
TURBINE OUTLET, ACFS	2594
AMMONIA RECIRCULATION FLOW RATE (EVAPORATOR INLET FLOW) LB/SEC	1324
FEED PUMP HEAD, PSI	41.8
RECIRC. PUMP HEAD, PSI	15.2
AMMONIA QUALITY, TURBINE INLET, %	100
AMMONIA QUALITY, TURBINE OUTLET, %	97.5
EVAPORATOR TEMPERATURE, °F	70
CONDENSER TEMPERATURE, °F	50
ENTHALPY DROP ACROSS TURBINE, BTU/LB (AT ASSUMED EFF. OF 85%)	16.8

HEAT EXCHANGER SUBSYSTEM	EVAPORATOR	CONDENSER
TUBE LENGTH - TOTAL, FT	29.83	29.83
TUBE OUTER DIAMETER, IN	1.00	1.00
TUBE WALL THICKNESS, IN	0.031	0.026
ENHANCEMENT RATIO, GEOMETRIC - I/D	1.46/1.50	1.46/1.50
NUMBER OF TUBES	42,667	43,883
SHELL DIAMETER (ID), FT	26.25	27.08
TUBESIDE WATER VELOCITY, FPS	6.61	5.82
TUBESIDE PRESSURE DROP, PSI	4.12	3.61
WATER INLET TEMPERATURE, °F	80	40
WATER OUTLET TEMPERATURE, °F	74.1	46.2
AMMONIA TEMPERATURE, °F	70	50
LMTD, °F	6.62	6.41
THERMAL DUTY, MBTU/HR	1543	1495
OVERALL HEAT TRANSFER COEFF., BTU/HR	896	796

POWER BUDGET

GROSS POWER, MWe	14.09
NET POWER, MWe	10.00
GROSS POWER/NET POWER	1.40
WARM WATER PUMPING POWER, MWe	1.35
COLD WATER PUMPING POWER, MWe	1.78
AMMONIA FEED PUMPING POWER, MWe	0.24
AMMONIA RECIRCULATION PUMPING POWER, MWe	0.14
CHLORINATION POWER, MWe	0.05
MECHANICAL CLEANING POWER, MWe	0.01
CONTROL, AMMONIA SUPPORT, MISC., MWe	0.46

FIGURE 2.4. NET POWER VERSUS AVAILABLE ΔT
(DESIGN $\Delta T = 40^{\circ}F$)

FIGURE 2-5. POWER SYSTEM COST VERSUS DESIGN ΔT

In order to perform tradeoff studies of cost versus design ΔT (which is selected as the annual average ΔT) it is necessary to know how the power system cost depends on design ΔT . A detailed analysis was carried out for the PSD-II design which is very similar to the PSD-I design. Figure 2-5, which is from this study shows the cost of the power system and the cost of the heat exchangers versus design ΔT . The curves shown were obtained using TRW's design and optimization model. The cost includes power system, support systems such as ammonia and nitrogen subsystems, and seawater pumps. The variation of the cold water pipe cost with ΔT was also included to properly account for increased water flow rates at decreasing ΔT . No packaging penalty was included. This is valid when the plantship size is driven by the deck space required by the process plant.

In the ΔT range of interest: 32°F (17.8°C) to 44°F (24.4°C), the power system cost curve is closely approximated by:

$$\frac{C}{C_{\text{Design}}} = \left(\frac{\Delta T}{\Delta T_{\text{Design}}} \right)^{-1.8} \quad (2-3)$$

The cost of the heat exchangers alone is closely approximated by:

$$\frac{C_{\text{HX}}}{C_{\text{HX, Design}}} = \left(\frac{\Delta T_o}{\Delta T_{o, \text{Design}}} \right)^{-2.6} \quad (2-4)$$

This dependence has been independently derived by Lavi(11) using a geometric programming model to minimize heat exchanger cost. Note that the above expressions are not valid for ΔT less than about 30°F (16.7°C). The equations above show that the system cost is less sensitive to the design ΔT than the heat exchanger cost. This is to be expected since a significant fraction of the power system cost is fixed or only marginally dependent on ΔT (e.g., generator, instrumentation and control, and ammonia support systems).

2.2 Hall Process Plantships

2.2.1 Problems with the Conventional Hall Process

Previous studies^(1,2) have assumed that an OTEC/aluminum plantship would employ conventional Hall cells as described in Section 1.3. The major technical problem associated with the use of a conventional Hall cell in a floating plant environment is that platform motion may cause the molten metal pad of aluminum at the base of the cell to move so as to contact the anode, as shown in Figure 2-6, shorting the anode to the cathode. Once the short has formed, a magnetic pinch effect holds the liquid metal in contact with the anode. Continued operation with an anode-cathode short reduces the cell efficiency. We have analyzed the issue of oscillations of the bath and molten metal in the Hall cell under periodic external forces and found that they were severe. It was thought that perhaps the magnetic fields present in the Hall cell, or which could be applied, would damp the motion of the conductive molten aluminum. However, it is found that $j \times B$ forces can damp the oscillations, but not eliminate them.

There are two options for overcoming this problem. The first is to stabilize either the platform or the cell, and the other is to use another reduction process which is more tolerant of motion.

Several methods of stabilizing the cells or the platform have been studied. Mechanical stabilization of the cells against rolling, pitching, and heaving motion would be an extremely difficult mechanical problem made doubly difficult because of the problems associated with providing flexible connectors for the fractional mega-ampere bus bars which connect each cell. There may be as many as 200 cells to be stabilized on a given plantship. There are several methods available for stabilizing the platform from pitch and roll. However, studies show that even if the cell or the platform could be stabilized against pitch and roll, the Hall cell would still be susceptible to shorting by sloshing, as shown in Figure 2-6, through heaving motion. It was found that dynamic methods for stabilizing floating platforms against pitch and roll generally result in increased heaving of the platform. For this reason, one is led to the conclusion that other reduction processes may be more suitable for use in the OTEC plantship environment. These alternate processes are discussed in Sections 2.3 and 2.4.

The material that follows in this section provides background information for those in the aluminum industry to evaluate a technology they know within the context of the OTEC environment. We discuss the OTEC power system integration, the issues of logistic support, discuss the prospects of heat recovery, the issues of fume control and cryolite recovery, and material on the drained cathode Hall cell process.

2.2.2 System Considerations

Due to the high cost of floor space and labor aboard the floating OTEC platform, as many functions as possible will be performed at the shore base, with only the function of operating the reduction cells and casting the metal into pigs (200 lb), sows (1000-2000 lb) or ingots (30,000 lb) being performed on-board the plantship. Because of difficulty in transferring heavy objects

FIGURE 2-6. CROSS-SECTIONS OF HALL CELLS WITH SODEBERG ELECTRODES SHOWING (A) ELECTRICAL SHORTING OF ANODE TO ALUMINUM METAL PAD DUE TO TILTING OF CELL BECAUSE OF MOTION AND (B) DUE TO SLOSHING.

between the plantship and the support vessels during heavy sea states, it may be desirable to cast the metal into small particles⁽¹²⁾ which can be transported through flexible lines between the two vessels.

In the following section, we will outline how the number of reduction cells, or pots, on the floating reduction plant would vary as a function of the anode current density. The purpose of this section is to outline how the other parameters in the reduction plant equation vary as a function of through-put; e.g., storage must be provided for 1) alumina, 2) anodes, 3) cryolite, 4) caustic soda for scrubbers, 5) replacement cathodes, 6) finished aluminum, 7) anode stubs, 8) cathode assemblies for rework, and 9) scrubber blowdown for cryolite recovery.

An important factor to be investigated by economic tradeoff calculations is whether the needed storage volumes should be provided on the floating plantship or on a possibly less expensive series of hulls or barges which would be moved alongside the plantship for semicontinuous loading or unloading.

The answer may depend upon whether the transport hulls must be manned at all times or whether they have their own propulsion systems. The following factors must be considered to determine the physical quantities involved in the nine commodities outlined above.

1. Alumina: Every ton of metal produced will require about two tons of alumina valued at roughly \$0.10/lbm. The normal inventory level at a shore plant is a 15 to 30 day supply. In the model we have assumed, if an x-day supply of alumina is to be maintained at the plantship, a comparable inventory will be required at the shore base, plus the quantity which is in transit.

2. Anodes: Approximately 800 lbm of carbon will be consumed per ton of aluminum metal. Each anode weighs about 1-1/2 tons. The anode requirement is about one anode per pot per day. The anode stems, which represent about 1/3 the total weight of the anodes, must be returned to the support base (commodity 7). The cost of the anode rod assemblies, roughly \$1000 each, must be factored into the capital cost and transportation relations.

3. Cryolite: Roughly 100 pounds of synthetic cryolite are required per ton of aluminum processed. The HF values are captured in the scrubber, and are returned to the shore base (as commodity 9) for regeneration.

4. Caustic Soda for Scrubbers: Roughly 10 lbm NaOH/ton of aluminum is needed in the wet electrostatic precipitators which recover the HF.

5. Replacement Cathodes: The useful life of a cathode assembly is 3 years, and for a typical plant having 180 cells, five will be replaced each month; the cathode rework will be accomplished at the shore support site.

6. Finished Aluminum: We have assumed that 99.5% pure aluminum ingots or particles will be the finished product of the OTEC plantship. (Although a specific alloy might be producible on the plantship, as a general case the product is assumed to be the commercial grade ingot).

7. Anode Stubs: Return of anode stubs to the shore plant reprocessing is a sizeable logistic load: 100 t/d for a 70,000 t/yr plant with 180 pots.

It will be desirable to have one shore support base supporting a number of floating OTEC/aluminum plantships. Thus almost all of the functions assigned to the plantship are linear with respect to capital costs in relation to the mass throughput. The functions assigned to the shore base benefit from the economics of scale. For the conventional Hall process on a floating plantship, there is no clear cut rationale, other than crew size, to determine a priori from the process standpoint an optimum size for the floating reduction plant. As we will see the optimum size is controlled by the plantship hull considerations.

2.2.3 Current Density Variation

The key variable for the reduction plant using the Hall process is the current density at the anode, j_a . In present commercial practice, j_a varies from 7 to 15 kA/m². Most new plants are now designed to operate in the lower current density region to obtain higher efficiency, while many older plants that were designed when energy was relatively inexpensive use higher current density, which reduces capital costs. Another key variable is the unit energy requirement, E , in J/kg (or kWh/lb) to produce a unit mass of molten metal. Since the current efficiency of the cells is practically constant over the range of commercial operation, E , can be represented over the range of interest by the linear relation:

$$E = 11.85 \times 10^6 + 5.095 \times 10^3 j_a \text{ (J/kg)}, \quad (7 \times 10^3 \leq j_a \leq 1.5 \times 10^4) \quad (2-5)$$

Once the plant mass flow or throughput, $\dot{m}$, in kg/sec, which can be derived from the annual production of the plant, has been decided upon, then Eq. (2-5) can be used to determine the net power requirement for the Hall cells by using the relation:

$$P = \dot{m}E \quad (2-6)$$

where:

$$\dot{m} = A_a \eta_c j_a \times \frac{26.97}{3F} \times 10^{-3} \text{ (kg)} \quad (2-7)$$

and

A_a = the total anode area, m²;

η_c = the coulombic efficiency, based on experience; assumed to be 90%

j_a = the anode current density, A/M²;

F = the Faraday constant = 96,402 coulombs/GAW;

3 = the charge of the aluminum ion; and

23.97 is the gram atomic weight of aluminum.

Equation (2-7) then reduces to:

$$\dot{m} = 8.398 \times 10^{-8} A_a j_a \quad (2-7A)$$

Thus, for an $\dot{m}$ of 3 kg/sec (104,000 T/yr) and j_a of 7×10^3 A/m², the required anode area is roughly 5000 m², which leads to estimates for the other physical parameters for the reduction plant. For example, if we assume 24 anode blocks of 0.71 x 0.91 m per cell, the anode area per cell, A_{cell} , is 15.6 m². We still assume the cells are connected in series so that the current is identical through each cell. The number of cells, n , is then given by:

$$n = \frac{A_a}{A_{\text{Cell}}} = \frac{5000}{15.6} = 320 \quad (2-8)$$

assuming the anode blocks in the cell are all in parallel, the total current through the cells, which are connected in series, is then given by:

$$I = j_a A_{\text{cell}} = 7 \times 10^3 \times 15.6 = 1.092 \times 10^5 \text{ A} \quad (2-9)$$

From eq. (2-6) we see that 142.8 MW are required to produce 3.0 kg/sec, and the potline needs 1.308 kV to drive the 1.092×10^5 A through the cells. To this must be added the voltage drop due to bus bar losses (about 2%) and ac/dc conversion losses. In conventional practice, the economics of ac/dc conversion generally determine the voltage to be used, which is usually less than 1000 V. For this type of installation on land, our example would be designed to operate as 2 lines each with 160 pots, in series, with 670 V/line.

The typical Hall cell requires a space of about 4 m by 9 m plus clearances of 2 m side to side and 10 m end to end, so that, the floor area per cell is 114 m² and the total cell floor area, A_f , is $n \times A_1 = 320 \times 114 = 36,500$ m². If we allow a height of 15 m to the ceiling to accommodate the fume collection system, and a depth of 2.4 m below the working level and 4.0 m above for the pot, the volume required for the hall plant reduction cells, V_r , is $2.14 A_f = 781,000$ m³. The typical baseline operating weight per cell is 10^5 kg, so the weight of the reduction equipment W_r is 320×10^5 kg or 32,000 MT.

2.2.4 Plantship Layouts

To examine various hull platforms which might encompass ranges of seakeeping abilities and structural moments in response to wave action, we examined the following plant configurations: single and dual-reduction-deck barges; single and dual-reduction-deck semisubmersible hulls; and dual-reduction-deck, circular spar hull.

For our initial baseline case we chose a plantship capacity of 70,000 MT/yr, which corresponds to a mass flow of 2.2 kg/sec and requires about 120 MWe of OTEC net power. This size is representative of a single potline of 160 to 180 Hall cells, which is more or less the industry's building block for expansion.

For Concept 1, Figure 2-7 there are six potrooms, each with 30 cells, arranged on either side of the OTEC power system. The hull length is 1100 ft. The cold water pipe, located in the center of the platform, feeds a cold water plenum which distributes the water to the condensers. Warm water plenums at the outboard edges of platform distribute water to the evaporators. The ammonia turboalternators are athwartships between the evaporators and the condensers. This arrangement simplifies access to the OTEC components for maintenance. Storage for alumina, anodes, etc., and finished aluminum is under the potrooms on a lower deck.

For Concept 2, Figure 2-8, the reduction cells are placed on two decks, which shortens the hull length to 714 ft and results in a smaller displacement.

In Concept 3, Figures 2-9 and 2-10, the single-deck, semi-submersible hull, the OTEC power system is located in the central section with the evaporators, condensers, pumps, and turbo-alternators located below the water surface. Alumina, anodes, finished aluminum, etc., are stored above the waterline on a deck below the potrooms. Sponsons are provided for support vessels to tie up to for loading and unloading.

Concept 4, Figure 2-11, the dual-deck-reduction plant on the semisubmersible hull has a length of 480 ft, compared to 900 ft for Concept 3, with a corresponding reduction in displacement.

Concept 5, Figure 2-12, with a rectangular, dual-deck-reduction plant on a circular spar hull, has a larger displacement than any of the other form concepts.

Table 2-2 summarizes the characteristics of the five plantships. For these Hall process cases, the hull cost is the major figure of merit on which to rate the various options, since the reduction plant characteristics far outweigh the OTEC power system requirements in determining the size of the hull. The dual-deck-reduction plants show 25% lower costs than their single-deck counterparts. Although plant operators, fearful of the consequences of cell bottom "burn through," prefer the single deck, this large cost differential makes the dual-deck configurations preferred.

Reinforced concrete hulls appear to have a cost advantage over steel hulls, in addition to a potential freedom from the problems of circulating currents when the magnetic fields associated with the fractional mega-ampere currents in the Hall process are changed. This will require care in construction to insure that the steel reinforcing bars in the appropriate sections of the concrete hulls do not provide continuous paths for circulating currents.

From Table 2-2 it may be seen that both of the semisubmersible hull designs have longer pitch, heave, and roll periods than the barge platforms. These increases in period, when compared with the design hurricane wave spectra for deep water, which peaks with a period of about 13 to 14 sec. lead to a marked improvement in platform stability at cost penalties of only 5%. This small difference in hull capital cost may be more than made up by the greater ability of the aluminum plant to operate at full capacity during bad weather.

Fig. 2-7 Concept 1: One Aluminum Production Deck, Rectangular Barge

Fig. 2-8 Concept 2: Two Aluminum Production Deck, Rectangular Barge

CONCEPT No. 3: SEMISUBMERSIBLE
ENCL. 8. 100% BLOCK

Fig. 2-9 Concept 3: Single Deck, Semisubmersible

Fig. 2-10 An Artist's Rendering of the Concept 3 Plantship

PRINCIPAL DIMENSIONS

Length = 480 ft Depth = 212 ft
 Breadth = 440 ft Draft = 132 ft

Fig. 2-11 Concept 4: Semisubmersible Hull, Two Aluminum Production Decks.

Fig. 2-12 Concept 5: Circular Barge
 Double Aluminum Production Deck

TABLE 2-2. Summary Characteristics of 70,000 MT/Yr JTEC/Aluminum Plantships Using Hall Process Reduction Cells with Anode Current Density of 7.0 kA/m²

	CONCEPT #1	CONCEPT #2	CONCEPT #3	CONCEPT #4	CONCEPT #5
	Single Dk. Barge	Double Dk. Barge	Single Dk. Semisub	Double Dk. Semisub	Circular Barge
<u>Principal Dimensions</u>					
Length (ft)	1,000	714	900	480	Diameter =
Breadth (ft)	440	440	440	440	430 ft
Depth to Mn Dk (ft)	90	90	212	212	
Transv. Lower Hull (LxBxH)	None	None	(1)-200x440x82	(1)-200x440x82	Height =
Longl. Lower Hulls (LxBxH)	None	None	(4)-200x100x52	(4)-140x100x52	182 ft to
Vertical Columns (LxBxH)	None	None	(2)-200x100x100 (8)-75x75x130	(2)-200x100x100 (4)-70x75x130	storage deck
<u>Operating Conditions</u>					
Draft (ft)	56.0	56.0	132.0	132.0	132.0
Displacement (lt)	706,306	436,096	506,971	357,028	547,687
Fixed Ballast (cy)	65,185	None	None	None	
Vert. Center of Gravity (ft)	28.65	44.06	87.56	97.07	111.83
Vert. Center of Buoyancy (ft)	29.05	28.49	53.51	54.93	66.0
Transv. Metacentric Height(ft)	307.84	303.93	53.58	46.39	38.95
Longl. Metacentric Height (ft)	1,930.0	811.2	194.97	37.09	
Transv. Gyradius (ft)	194.0	176.0	152.0	147.0	118.0
Longl. Gyradius (ft)	328.0	214.0	201.0	88.0	
Roll Period (sec)	12.25	11.2	23.0	24.0	21.0
Pitch Period (sec)	8.27	8.33	16.0	16.0	
Heave Period (sec)	8.18	8.0	16.0	15.8	13.0
<u>Stability</u>					
Required Transv. Metacentric Height(ft)		2.16		2.05	1.35
Required Longl. Metacentric Height (ft)		1.71		1.99	
Dynamical Stability Transv.		204 Ft-Deg		6.1	A+B/B+C = 8.4
Dynamical Stability Longl.		209 Ft-Deg		4.96	
<u>Hull Cost</u>					
All Steel (Millions)	288.3	203.9	279	215.9	
Concrete/Steel (Millions)	229.6	186.6	244.3	195.8	230.63

Furthermore, for a given weather condition, the greater stability of the semisubmersible platform will favor safety in the molten metal operations such as casting, and the greater stability may ease the problems of designing the CWP and mooring systems. In combination, these considerations lead to a judgement that the semisubmersible hull with a dual-deck-reduction plant will be the preferred configuration when all of the aspects of lifetime system cost and reliability are taken into account.

Systems costs may be reduced further by using techniques which can reduce the size of the reduction plant such as increasing the anode current density, which will reduce the number of cells required for a given annual production, and hence the weight and volume of the reduction plant (but at the expense of energy efficiency). This option is examined as part of the drained cathode Hall cell plantship discussed in Section 2.3.

2.3 Plantship Subsystems

2.3.1 Waste Heat Recovery

The Hall reduction process is relatively inefficient: only about 40% of the electrical energy is used in the reduction reaction and about 60% of the input energy appears as heat in the cell which must be dissipated to the environment. This waste heat is available at temperatures of up to 300°C and can be used in a secondary thermodynamic cycle to generate additional electrical power as has been suggested earlier (e.g., Ref 1). Assuming that 80% of the waste heat could be recovered, and that a Rankine cycle rejecting the heat to 4°C water brought up through the cold water pipe could achieve 65% of current efficiency, we estimate that 15% of the waste heat could be recovered as usable electricity; however, this would require a major redesign of the Hall cell.

The schematic diagram of the present Hall cell shown in Figure 2-13 includes typical surface temperatures at various parts of the cell.⁽¹³⁻¹⁵⁾ The input to such a cell is 450 kW, and the losses are about 270 kW. The lost energy is divided among the various surface energy fluxes and the exhaust gases according to the proportion arrived at in earlier studies. Three options for heat recovery were considered:

- 1) Freon 12 superheated to 700 psia, 440°F, and expanded to 100 psia, 80°F; such a cycle is suitable for land-based applications.
- 2) The outlet pressure and temperature were changed to 60 psia and 50°F, making it suitable for OTEC applications.
- 3) Superheated ammonia with 300 psia, 200°F at the inlet and 80 psia, 50°F at the outlet; these conditions are also suitable for OTEC applications.

The recovery efficiencies (energy recovered as a percentage of the energy lost by the cell), Table 2-3 show that Option 2, shown schematically in Figure 2-14, the best recovery efficiency. In practice, the heat recovered from many cells would be recovered in an optimized turbine.

Through the use of the single point feeder concept⁽¹⁶⁾ it may be possible to trap the hot gases which are generated at the anode and to efficiently recover this heat energy. The emphasis in previous designs has been to draw in large quantities of diluting air to the cell to ease the fume control problems.

Efficient heat recovery will require extensive cell design modifications to allow the thermodynamic working fluid to be heated directly by the cathode and other structures (rather than depending solely on recovering this energy from cooling air) while maintaining the required thermal balance within the cell. These modifications would increase efficiency and lower capital costs. The technology is available, but in the past there was little economic incentive to employ it because of the low cost of electricity at most reduction plants.

FIG. 2-13. HALL CELL HOOD CONFIGURATION AND GAS TEMPERATURES FOR HEAT RECOVERY PURPOSES

FIG. 2-14. SCHEMATIC OF THE FREON 12 POWER CYCLE

TABLE 2-3 ENERGY RECOVERY EFFICIENCIES

No.	Working Fluid	Application	Recovery Efficiency, %
1.	Freon 12	Land-based plants	11.7
2.	Freon 12	OTEC plantships	13.1
3.	Ammonia	OTEC plantships	7.8

For OTEC reduction plantship applications, the economics are different. The basic OTEC power plantships (before adding the aluminum plants) projected to cost about \$3000/kW_e. It therefore appears appropriate to spend an amount up to \$3000 per electric kilowatt recovered for waste heat recovery. The heat recovery option has not been included in the economic models discussed in Section 3; however, the mechanism to do so is in place. Further work in this area appears warranted.

2.3.2 Plantship Fume Control/Cryolite Recovery

Options for the potroom fume control exhausts range from free release into the atmosphere to complete treatment using one of the available commercial proprietary systems which recovers alumina dust and the fluorides. In many cases the plantship will operate at least 100 miles offshore; 150 miles is perceived to be near the farthest distance from which the OTEC power would be sent by cable to shore (the distance from Tampa, FL, west to the continental shelf in the Gulf of Mexico). For such large distances from shore, or even greater distances that might be economically practical for cruising plantships, it is not established what environmental air quality standards would apply. For this reason, we have adopted as a baseline design the concept of using wet scrubbers, with sea water being the scrubbing medium. The scrubber exhausts will be vented to the atmosphere through a stack which discharges the effluent above the immediate plantship vicinity. The trade-offs in this case are that, in addition to lower capital costs compared to a complete treatment system, there is a substantial reduction in the amount of power required for the scrubber system, but larger quantities of fluorides must be provided for electrolyte makeup.

2.3.3 Backup Power Requirement

A number of the OTEC studies examining the use of OTEC power in the electric utility grid have assumed an availability of 80%, similar to the availability of fossil fueled plants. When the generating plant is connected to the grid, there is usually some excess generating capacity and a seasonal variation in the load so that some of the generating units can be taken off the line for maintenance. However, an aluminum plant requires continuous power availability at almost 100% load factor.

The Hall process alumina reduction plant operates with the bath at a carefully controlled temperature of about $945 \pm 5^\circ$. The temperature is determined by a balance between the input power, the heat of reaction, and external heat losses. If for some reason the input power is reduced to less than 95% of its nominal value for an appreciable period of time, production of aluminum will stop and the cell will cool down. Below about 940°C , the entire bath will be frozen and lose its electrical conductivity. Once this happens, the solidified bath must be removed by mechanical means (usually a jackhammer) and the cell restarted using molten bath and metal from an external source, a lengthy, time-consuming process. It is, therefore, extremely important to keep the potline energized at nearly full power so that the required temperature can be maintained. For this reason, it is important to provide "excess" capacity for the OTEC power system components so that nameplate output rating can be maintained almost 100% of the time, even when

major components such as heat exchangers are down for maintenance or cleaning, etc. Designs which favor cleaning methods which do not require the OTEC power system output to be reduced during cleaning operation appear to be favored.

It is then essential that some auxiliary power system be installed which will have enough capacity to allow the plant to be shut down in an orderly fashion if there is a catastrophic failure of the OTEC power system. The lowest-capital-cost, standby generating systems are powered by gas turbines because they can be brought on the line quickly. Gas turbines weigh much less and take up less space than diesel engines. Another concern is the potential reduction in OTEC power that might occur due to upset of the thermal gradient by a major storm, reducing the available ΔT . For these reasons, the provision of an alternate power generation source is a must. The alternate power system of 2 MW or so that is required to get the OTEC power system started could provide part of this standby capacity. The major uncertainty is how much fuel to provide, and how much heat recovery equipment should be included in the standby power system. We conclude that about 100 MW of output will be required from the standby power system for an OTEC/aluminum plant-ship. The input to the potline can be reduced for short periods to allow circulating pumps to be restarted, etc., so the full 40 MW required by the OTEC power system auxiliaries may not be required as additional standby capacity. This level can be determined during the power system preliminary design.

Once the projected plantship siting area has been selected, historical records can be examined to determine the probable time extent of a thermal gradient upset, so the amount of required onboard fuel can be determined. We have assumed that fuel for the 15 days full power operation will be adequate. This scenario envisions shedding or dropping the CWP during a storm, followed by recovery and reconnection of the CWP, an operation could take 30 days or more, during which the reduction plant would have to operate on the gas turbines. The onboard fuel required would depend upon how soon after the storm (assumed 5 days duration) could fuel for the gas turbines be supplied from a shore support base.

With regard to the justifiable extent of heat recovery from the gas turbine system exhaust gases, it is conceivable that the OTEC/aluminum plantship would operate in a hybrid mode with the gas turbine system providing part of the required power during those parts of the year when the OTEC power output is limited because of seasonal variations in the available ΔT . Numerous heat recovery or combined cycle options available ranging from using a recuperator to preheat the combustion air to reduce the fuel requirement, through the use of a bottoming Rankine cycle, to rejection of the waste heat to the OTEC ammonia cycle. The extent to which any of these options can be justified will depend upon the short-term and long-term temporal variations in ΔT , the cost of additional OTEC power system capacity, and the cost of fuel. The optimum configuration of the hybrid system may be very site-specific. At this time, all we can state is that further work in this area will be required.

Integration of gas turbines and OTEC turbine systems is shown in Figure 2-15 which is a one-line electrical diagram of one OTEC/aluminum studied plantship, one with a potline that requires 218,000 A with a voltage drop of 440 V. The reduction plant has various auxiliary loads such as an air compressor, lighting, cranes, fume control, etc. The OTEC power system has warm water, cold water, and ammonia circulation pumps for each module. Plantship loads include the hotel, cranes, conveyors, etc. To keep the switchgear cost down, it was deemed advisable to combine the OTEC power systems into five groups of two generators each at the 13.8-kV level with outputs being combined at the d.c. bus. Therefore, four of the groups (with backup gas turbine driven generators) would feed the d.c. bus through individual transformers and rectifiers, while the fifth group would feed the 4160 V bus to provide power for the warm water pumps, ammonia compressors, the reduction plant auxiliaries, and the other OTEC system auxiliaries. For emergency power and OTEC power-system or gas-turbine system starting requirements, a diesel-driven generator system is provided. In an actual plant design, each group of generators could be connected to the 4160 V bus.

In the event that the available ΔT is reduced, part of the load can be picked up by one or more of the gas turbines. A drop in ΔT would reduce the OTEC ammonia turbine outputs, but would not reduce the requirement for auxiliary pumping power. As ΔT continues to drop, a point is reached where the ammonia turbine output is only equal to the pumping power, and at this point the OTEC ammonia system would be secured and all of the electrical power would come from the gas turbines.

Inasmuch as the gas turbine system will already be in place for standby service, there may be a tradeoff which would result in better economics if a hybrid system is considered. In this case, the OTEC power system is designed to provide 100% output at some maximum ΔT , which would minimize the cost per kilowatt of the OTEC system, and the gas turbines are used to make up the difference in output when ΔT is below the design value. As an example, Figure 2-16 shows the monthly variation in ΔT at Punta Tuna, Puerto Rico, given in Table 1.1. The average ΔT is 21.3°C while the peak month is 22.7°C and the lowest month is 20.0°C. Using the -1.8 power scaling law,⁽⁹⁾ the costs per kilowatt when designing for $\Delta T = 20.0^\circ$ should be about 25% more than when designing for $\Delta T = 22.7^\circ\text{C}$; for the later case the gas turbine system can operate to keep the net output up to 100 MW at all times by keeping the fuel and operating expenses equivalent to 28.5 MW on an annual basis. Tradeoff studies may suggest a compromise design ΔT between the maximum ΔT and the average ΔT for other designs. Efficient accomplishment of this part load operation will require that at least two of the gas turbine systems be dual-shaft units so that the compressor can be operated efficiently at the speed appropriate for the power being produced.

FIG. 2-15. OTEC/ALUMINUM PLANTSHIP
ONE LINE ELECTRICAL
DIAGRAM

Fig. 2-16.A MONTHLY TEMPERATURE DIFFERENCES AS ΔT 1000m
AT PUNTA TUNA, PUERTO RICO

Fig. 2-16.B MONTHLY OTEC POWER SYSTEM OUTPUTS AT
PUNTA TUNA, PUERTO RICO

2.4 Drained-Cathode Hall Cell, Floating OTEC/Aluminum Plantship

2.4.1 Introduction

The use of the drained-cathode Hall cell⁽¹⁷⁾ (Figure 1-10) on the floating OTEC/aluminum plantship has a number of advantages which make it more suitable for the maritime environment than the conventional Hall-Herault cells. The carbon on the cathode surface is covered with a refractory metal alloy or compound which serves as the cathode in place of the molten aluminum metal "pad" used in the conventional Hall cell. As the aluminum is formed, it flows by gravity into the central reservoir from which it is removed periodically, thus the name "drained cathode." Since there is no metal pad, the anode and the cathode can be brought closer together which makes the cell more efficient by reducing ohmic losses in the electrolyte "bath." From the conductivity of the bath, we know that reducing the anode to cathode spacing by 0.025 m (1 inch) will reduce the cell operating voltage by 1 volt. Thus, if the cell was operating with a 6-v drop, reducing the anode-cathode distance by 1 in. would allow it to run at 5-v for the same current, saving electrical energy per unit mass of metal produce. Practical limitations determine the minimum anode-cathode distance; in the conventional Hall cell, one of these is motion of the metal pad in response to magnetic forces. By eliminating the metal pad, the drained-cathode cell allows the anode-cathode spacing to be reduced. The result is that the cell is more energy-efficient and can be operated efficiently at higher current densities, so that fewer cells are required, and the size and weight of the reduction plant and hence the support hull are reduced.

A significant characteristic of the drained-cathode Hall cell is its relatively insensitivity to plantship motion. If the aluminum storage well is constructed with appropriate anti-sloshing baffles, the cell should not short out during moderate pitching, rolling, or heave motions of the plantship. Thus, least expensive, barge-type hull may be used instead of semisubmersible or stabilized type platform. However, the molten bath might still slosh around inside of the cell. While the cells could be designed to have more freeboard and could tolerate more motion, this would complicate cell operations without insuring that the bath would never slosh out of the cell under extreme conditions. Allowing the bath to escape from the cell has serious safety and economic considerations. Therefore, an entirely new cell design may be required for operation on an OTEC plantship; this area warrants further study. Pilot testing of such a new design at sea, or in a motion simulator before deployment, would appear to be prudent course of action.

We must also ask what the sensitivities of other systems in the plantship complex are. For example, falling-film heat exchangers would suffer a degradation in performance at some level of platform motion. This could be compensated by operating the standby gas turbines. Therefore, there is a possible tradeoff of hull stability vs fossil fuel consumed over the lifetime of the plantship.

The only other system which appears sensitive to plantship motion is the casting system where liquid aluminum is poured into molds to solidify. To reduce the plant area required for the cast house, and to keep the crew size small, we have assumed that the molten metal, after being removed from the

drained cathode pots by a vacuum "snorkle" would then be cast into 500-kg "sows" in open molds, allowed to solidify and cool, and then placed in storage awaiting the arrival of the shipping vessel or barge. Casting of the liquid metal on a heaving and pitching deck might present a safety hazard. There are two apparent choices: 1) provide sufficient metal storage capacity in the wells of the drained-cathode cells so that casting could be curtailed during periods of violent weather which might last several days, or 2) provide a pressurized casting system similar to those used in the die-casting machines, where the metal is totally enclosed and is transferred by a combination of gravity and applied hydrostatic pressure. However, we should note that the metal removed from the pots will be about 950°C, whereas most die-casting operations are conducted with the metal near its melting point of 720°C; therefore a special casting technology may have to be developed if this route is to be followed. This technology could include a secondary heat recovery cycle, leading to more power production. An analysis of hull dynamics in various sea states and the expected probabilities and duration of these sea states in the chosen deployment area will be needed to establish criteria for selection of casting methods.

Thus far, we have assumed that the motion of the bath in the drained-cathode cell would not have a deleterious effect on the cells performance. In fact, some cell motion might be desirable as a method of expediting the removal of gases from under the anode surface. As previously discussed, the cell motion cannot be allowed to be so large that the bath would slosh out of the cell, which would be most likely to happen when the frozen crust over the bath was being broken for the purpose of adding alumina. This possibility can be mitigated against by using single-point alumina feeding (as described in Reference 16). The single-point feed does not require the entire length of the crust to be broken, and the remaining crust over the majority of the bath surface will damp sloshing considerably. Single-point feed also requires less labor (the frequency of crust-breaking with a pneumatically driven tool, usually once every eight hours, is greatly reduced). By the time OTEC/aluminum plantships are operational, single-point feeding may be widespread throughout the aluminum industry.

Alumina feeding is usually performed by via a transfer hopper suspended from an overhead crane. The consequences of spilling the inert alumina due to platform motion are not severe. However, it would be prudent to design sufficient cell alumina storage capacity in the cell alumina bins so that replenishment could be expected to be suspended during periods of extreme weather.

Before discussing design of an OTEC/aluminum plantship using the drained-cathode technology, let us point out that no drained-cathode Hall cells are yet in commercial operation. Kaiser Aluminum is in the preliminary stages of investigating, under DOE sponsorship, the use of refractory hard metals for drained-cathode cells for a conventional reduction plant. Hence our performance and cost estimates must be based on reasonable guess extrapolations of conventional Hall cell technology for which there is a substantial cost and performance data base.

2.4.2 Plantship Sizing

We will assume that 3-phase, 60 Hz alternating current is produced by a 100-MWe OTEC plant at one of the standard generator voltages, i.e., 13,800, 4,160, or 2,500 V and is transformed down to the proper voltages and rectified to d.c. for input to the potline as shown earlier in Figure 2-15. Such an arrangement will simplify the introduction of supplementary power from the auxiliary gas turbine power supply in the event the OTEC power system output is reduced because of unscheduled maintenance, disruption of the thermal gradient by storms, etc.

For this study, we will assume an anode current density j_a of 14 kA/m^2 (9 amp/in^2), and a coulombic efficiency of 90%. At this j_a , a conventional Hall cell plant would require about 5.19 V per cell, including a busbar drop of about 0.150 V/cell. It will be assumed that through the use of the drained-cathode cell and a larger busbar to reduce losses, the cell can operate at 4.06 V leading to an energy requirement, E , of 13.43 kWh/kg (6.02 kWh/lb_m) of molten metal.

If we have 1/2% transformer losses and 2% rectification losses, the 100 MW of electrical input would provide $8.55 \times 10^8 \text{ kWh/yr}$ at 100% load factor. At the rate of 13.43 kWh/kg, plant production will be 63,640 MT/yr of metal, a mass flow near 2 kg/sec, with a coulombic efficiency of 90%. This will require 1675 m^2 of anode area for $j_a = 14 \text{ kA/m}^2$. If a conventional pre-baked cell configuration of 24 anode blocks is assumed, where each anode block has an area 0.065 m^2 , then the total anode area per cell is 15.6 m^2 , calling for a 108 cells. This number can be varied with slight changes in j_a to get the plant to fit in a prescribed configuration. For example, increasing j_a to 15.1 kA/m^2 (9.74 A/in^2) would allow a configuration of about 100 cells to be used with an increase of about 4% in required input power. For optimization studies, we can assume that the energy, (kWh/kg) per unit mass of metal, E , in the drained-cathode cell is given by:

$$E = 9.29 + 3.05 \times 10^{-4} j_a \quad (\text{kWh/kg}) \quad (2-10)$$

Following our previous practice with the Hall-cell plantship, we assume that the typical drained-cathode Hall cell occupies a space of about 4 m x 9 m. However, because the drained cathode Hall cell does not have a molten metal pad between the anode and cathode, it should be more tolerant of stray magnetic fields due to the busbar currents. For this reason, it may not be necessary to have as large a spacing between the cells as in the conventional Hall cell plant. Under these conditions, the cell spacing will be controlled by the requirements for mechanical access required for loading, unloading, and maintenance of the cell. It will be assumed that a clearance of 2 m side to side, 2m from the building wall, and 4 m end to end will be adequate for the drained cathode cell. Therefore, each cell will occupy a space 6 m by 13 m, or 78 m^2 . The total floor area required for 108 cells is 842 m^2 . One possible potroom configuration is to have three potrooms with 18 cells on each side of the potroom central aisle. Other possible configurations are one potroom with 54 cells on a side, making the potroom 326 m long and 26 m wide, or two potrooms side by side, 164 m x 52 m. A slight reduction in the spacing between pots could reduce the potroom length to 152 m. Another alternative is to provide two potrooms with 3 rows of cells each, with

the fume-control system routed downward. This configuration reduces the length to width ratio of the platform and may result in a lower hull cost.

Each bay of the potroom is provided with one 5-ton and one 20-ton overhead crane. The small crane is used for collecting the liquid metal and delivering it to the cast house, which is located at the end of each bay; alumina replenishment; replacing the prebaked anodes using an anode changing device; etc. The larger crane is used for performing maintenance on the cell, or removing the cells for replacement. The prebaked anodes will be brought out from the shore base and the stubs returned for refurbishment and reuse. At $j_a = 14 \text{ kA/m}^2$, about 1.5 anodes per pot per day will be consumed, or 162 per day for our 63,500-MT/yr drained-cathode plantship. The anodes weigh about 1500 kg, of which 500 kg is the iron stem. Each cell will have a mechanized ore feed system and a single-point-feed, mechanized crust breaker. An automated system will control the alumina feeding and setting of anode-cathode distances. If large reservoirs for molten metal are provided in the cells so that they need only be tapped once a day, it should be possible for a crew of three workers and one supervisor to man the potroom and the cast house.

The potroom activities will be backed up by an analytical laboratory which monitors product composition and bath composition. The analytical laboratory will be manned for only one shift per day. It will also be necessary to provide a maintenance shop, which could be combined with the OTEC power plant maintenance activities. The major maintenance activities in the plantship potroom will be maintenance of the overhead cranes, preventive maintenance of the electrolytic cell super-structure, and maintenance of the ore feed and crust breaker systems on a remove and replace basis. Cell cathode refurbishment, component repair, and any other major maintenance activities will be conducted at the shore support base.

The potroom will be connected to the OTEC power plant through the rectifier transformer system. The 108 cells at 4.06 V each will require 400 Vdc with the cells connected in series. The current density of 14 kA/m^2 times the anode area of 15.6 m^2 per cell leads to a busbar current of 218 kA. A transformer converts the generated voltage to $362 \text{ V}_{\text{rms}}$ to feed the rectifier bridge which will produce 400 Vdc. The fields for the ammonia-driven generators in the OTEC power plant will be controlled to produce the power required by the potline, so that tap changing transformers or saturable reactors for potline control will not be required.

The characteristics of the drained-cathode Hall cell plantship are compared with those of the conventional Hall cell and aluminum chloride plantships in Section 2.5.

2.5 Aluminum Chloride Reduction Process Plantship

The aluminum chloride reduction process is claimed to be more energy efficient than the conventional Hall process, and because of its physical design it should be more tolerant of plantship motions. It also will require less deck area. This section establishes a preliminary design for an OTEC/aluminum chloride reduction plant having a production capacity of 78,260 MT/yr of 99.5% pure aluminum ingot.

2.5.1 Chloride Reduction Process

The basic process presented in this section follows the Alcoa patents (18-27) where high purity alumina is coated with carbon in a fluidized bed reactor, then chlorinated to produce AlCl_3 and carbon oxides. The AlCl_3 is then reduced to aluminum metal and chlorine in a bipolar electrolysis cell. The chlorine is then recycled to the chlorination step for reuse as shown in Figure 2-17. The complete process and mass balance starting with bauxite are shown in Figure 2-18. Later we will examine other methods for producing AlCl_3 . For the purpose of this section, the source of AlCl_3 is not important.

For the OTEC application, there are several options where the various operations will be carried out. In the first Option (I) Figure 1-12, we will consider the coating of the alumina particles with carbon and the chlorination steps would be accomplished at the shore base producing AlCl_3 , which is then transported to the OTEC/aluminum plantship for reduction. The chlorine and any electrolyte which must be recycled are shipped back to the shore base for reuse and reprocessing. In Option II, Figure 1-13, it is envisioned that coating of the alumina particles with carbon would be accomplished at a shore support base. The pretreated alumina would then be transported to the OTEC/aluminum plantship for the chlorination and reduction process. Option III, Figure 2-19 starts with kaolin clays which would be calcined at the shore base, then moved to the plantship along with the carbon, presumably green coke, for chlorination and reduction.

In Options II and III, the plantship is made more complex by the requirement to incorporate the chlorination process; however, the transportation and handling of AlCl_3 and Cl_2 are avoided. A determination as to which option is the most favorable for the OTEC application, and under what conditions, is beyond the scope of this study.

Option I, for the assumed 78,269 MT/yr output, requires transportation of 1059 MT/d of AlCl_3 to the OTEC/aluminum plantship and return about 845 MT/d of liquid chlorine to the shore support base. Liquid chlorine is routinely transported in pressurized tanks aboard barges and, aside from its toxicity, presents no problems. Transportation of AlCl_3 , however, presents a slightly more difficult problem in that the material will react with water, it is similar to sodium hydroxide where mixing with water produces heat. In addition, the reaction of AlCl_3 with water produces Al_2O_3 which if processed in the bipolar reduction cells, will attack the carbon electrodes, releasing CO and CO_2 , which may require early replacement of the bipolar electrodes. For these reasons, it is desired to keep the AlCl_3 as dry as possible during its transportation, transfer, and storage.

All options require the shipment, on the average, of 214.3 MT/d of aluminum metal from the plantship to its destination for sale or conversion into consumer products.

In the second option, 548 MT/d of carbonized Al_2O_3 would be transported to the OTEC/aluminum plantship, and there would be no backhaul to the support base. As shown in Figure 2-17, the chlorination process is carried out

Fig. 2-17 Overall AlCl_3 Process Flow Chart

ALUMINUM PRODUCTION — CHLORIDE PROCESS

Fig. 2-18 Aluminum Chloride Reduction Process Mass Balance

FIG. 2-19. PRODUCTION OF ALUMINUM ON OTEC PLANTSHIP BY CHLORIDE PROCESS, INCLUDING ONBOARD CHLORINATION OF KAOLIN CLAYS OR BAUXITE - OPTION III

FIG 2-20. ALUMINUM CHLORIDE REDUCTION PROCESS ABOARD AN OTEC/ALUMINUM PLANTSHIP SHOWING WHERE WASTE HEAT IS AVAILABLE

at temperatures of 700°C to 900°C. The energy required to chlorinate the Al_2O_3 to AlCl_3 is about 0.37 KWh/kg Al. It is contemplated that this energy will be provided on the OTEC/aluminum plantship from the OTEC power system. Assuming an efficiency of 67%, the energy input to the chlorinator would be 4 MW. If we assume that the chlorine reduction process will require 11.45 kWh/kg Al, or 102.2 MW to produce 2.48 kg/sec of molten metal, the total OTEC power required will be 106.2 MW.

The issue is whether the waste heat in the chloride process be efficiently recovered in a waste heat utilization cycle to lower the capital cost of the OTEC power system. Figure 2-20 depicts the aluminum chloride reduction process to be accomplished under Option I including a number of places where water cooling is incorporated in the cycle. A detailed heat balance shows that 21% of the input energy is available in the cell coolant stream at 200°C. We may note that Freon 12, or ammonia, may be substituted for cooling water at the various places where H_2O is shown. If this heat can be recovered by bringing the secondary working fluid temperature up to near 500°C (the cell is at 700°C), and if the secondary working fluid can be incorporated in a 20% efficient cycle, the required energy input will be reduced to 4.68 kWh/lbm Al. This reduces the OTEC power system requirement to 82.3 MW plus whatever power is required to operate the pumping and recycle systems.

To estimate the space required by the chloride reduction process equipment, we can use the relationship derived in the previous section for the production rate, $\dot{m}$, and anode current density, j , i.e., $A_c = 1.191 \times 10^3 \dot{m}/j$. (18) We find that, for $j = 13.7 \text{ kA/m}^2$, as taught in the patents of Haupin, (26) and Russell, (26) and the desired $\dot{m}$ of 2.22 kg/sec, the required cathode area for the chlorine process is 2000 m^2 .

Figure 1-11, from LaCamera's patent, (22) shows a configuration for an aluminum chloride reduction cell in which bipolar plates are arranged in horizontal layers in the electrolyte bath. The current flow is such that the top surface of each bipolar plate acts as a cathode, depositing the liquid aluminum, while the bottom surface acts as an anode liberating chlorine gas. The chlorine gas rises to the surface while the molten aluminum drains to the bottom of the cells. Following LaCamera, we will assume that there will be 13 plates per cell; 11 bipolar plates, an anode plate on top and a cathode plate on the bottom, for the equivalent of 12 bipolar plates per cell stack assembly giving about 100 m^2 of cathode area per cell. We assume that each cell stack assembly will be about 4 m x 4 m in floor plan area, with a height of about 8 m. Twenty cells would be required for the desired output (Figure 2-21), and they can be placed closer together than the Hall process cells because magnetic effects are not as important.

Aluminum chloride and electrolyte feed, as well as molten aluminum removal and chlorine venting, can be done through ports in the roof of the cell as illustrated in Figure 1-11 although metal removal and cell draining could be accomplished through a hole in the bottom if desired. The cells will weigh about 200 MT apiece and are surrounded by water-cooled jackets. Therefore the cell spacing can be appropriate to high-priced real estate aboard the floating platform.

FIG. 2-21. 20 BIPOLAR CELL STACK ASSEMBLIES FOR 78,000 MT/YR ALUMINUM CHLORIDE REDUCTION-PLANT

2.5.2 Energy Balance of the AlCl_3 Reduction Cell

Since there is a paucity of data on the aluminum chloride reduction process, when compared to the 100-year old Hall-Heroult technology, it may be well to derive energy balance for the AlCl_3 cell from first principles. Following Loutfy's analysis,⁽²⁸⁾ Figure 2-22 shows the components of energy required for the production of aluminum by electrolysis of aluminum chloride. The ordinate is the charge required, in Faraday's per mole of aluminum, while the abscissa is voltage. The areas of the rectangles are proportional to the supplied energy components. In this figure, $-\Delta G^\circ/ZF$ indicates the theoretical minimum reaction voltage, and $-\Delta H^\circ/ZF$ denotes the enthalpy change for the reduction at the specified reaction temperature, T . The term $-\Delta H^\circ_{\text{tot}}/ZF$ is the enthalpy change for the transformation of the reactants at 298°K to the reaction products at temperature T . In Figure 2-22, 2.13 volts is required to maintain the cell at its temperature if there are no external heat losses (100% current efficiency). The terms E_{OE} , E_A , E_C , E_{OC} and E_{OA} in Figure 2-22 are the ohmic potential drop in the electrolyte, anodic overvoltage, cathodic overvoltage, and cathodic and anodic hardware ohmic losses, respectively. The sum of these terms can be considered to be equal to the total electrical energy losses of the reaction. The current inefficiency leads to an additional energy loss as shown. A part of the electrical energy losses is used to keep the reaction isothermal and to heat the incoming AlCl_3 .

The parameters shown in Figure 2-22 are used to determine the heat balance for a cell, which is shown in Figure 2-23. With the reported current efficiency of 0.90 and 3.3 volts per cell, the energy input requirement is 10.91 kWh/kg Al. The enthalpy contained in the aluminum metal which is Figure 2-20 removed from the cell is 0.197 kWh/kg Al, and the enthalpy in the vented chlorine is 0.38 kWh/kg Al. With the energy of reaction equal to 8.42 kWh/kg Al, the excess heat which must be removed from the cell is 1.913 kWh/kg Al.

For an electrical input of 100 MWe, the heat which must be removed from the cell stack assemblies is 22.7 MW_t. The temperature of the coolant from the cell stack assembly depends upon the maximum operating temperature of the inner shell of the cell stack assembly which is in potential contact with chlorine gas in the interior of the cell. If we assume that this temperature can be 125°C, and that the cycle would use cold water from the OTEC system for heat rejection, the potential Carnot efficiency is 30%. If 60% of the Carnot efficiency can be realized, about 4.0 MW of electricity can be recovered. Heat recovery from the chlorine vented from the cells could produce about an additional megawatt of electricity.

Some additional work is required on the chloride process heat balance to determine how much energy is required for reprocessing electrolyte which is described in Reference 19. It is estimated that this requirement is less than 1 MW.

Fig. 2-22 Components of Energy Required for the Production of Aluminum via AlCl_3 Electrolysis (973 K)
 (F is Faraday; E_{OE} = ohmic loss in electrolyte;
 n_A = anodic overvoltage; n_C = cathodic overvoltage;
 E_{OA} = anodic ohmic loss; E_{OC} = cathodic ohmic loss.

Fig. 2-23. Heat and Mass Balance for Aluminum Chloride Reduction Cell

2.5.3 Alternate Aluminum Trichloride Production Processes

The teachings of Russell⁽²⁰⁾ and Pope⁽²³⁾ discuss various methods for impregnating alumina with carbon prior to chlorination. From the patent literature, other authors⁽²⁸⁾ have assumed that the Alcoa Chloride process has the configuration shown in Figure 2-24. Bayer alumina is chlorinated to convert it to AlCl_3 which is electrolytically reduced to aluminum metal. The carbon comes from Number 6 (residual) fuel oil which provides the heat of reaction through partial combustion, with the residual carbon coating the alumina particles as described by Russell. The hydrogen in the fuel oil which is not burned is presumed to combine with chlorine in the chlorinator system to form HCl , which is presumably available as a byproduct for sale. The residual stream from the chlorinator, consisting of unreacted Al_2O_3 and impure AlCl_3 or other compounds is oxidized with pure oxygen to release the chlorine for recycle to the chlorinator, while the oxidized product is cleaned up and recycled after calcining. The patent literature⁽¹⁹⁾ describes techniques for cleaning up and recycling the sludges from the electrolysis cells. Chlorination of metal oxides in the presence of carbon in fluidized beds is a well established art and is commercially available technology, although care must be taken in the selection of materials for operation in a chlorine atmosphere at 900°C . In addition, it may be rather simplistic to assume that HCl is the only compound formed by the hydrogen which is introduced with the fuel oil. Nevertheless, it is understood that Alcoa operated both the chlorination and reduction portions of this process at their Point Comfort, Texas plant at the 33,000 t/yr level for about 3 years before the work was suspended for unspecified technical reasons.

An alternate method for producing aluminum chloride was originally proposed by the Toth Aluminum Corporation as a method of extracting the equivalent of Bayer alumina from kaolin clays. The process modified to the configuration shown in Figure 2-25 is well suited to the production of AlCl_3 from either bauxite or alumina rich clays; the clay is heated to drive off water vapor, then chlorinated in the presence of carbon at 900°C . The output from the chlorinator is sent to a countercurrent separator where the components with the highest boiling points, AlCl_3 , FeCl_3 and NaCl are removed, next, a second countercurrent separator removes the TiCl_4 and SiCl_4 . The tail gas, primarily carbon oxides, is vented to the atmosphere after clean-up.

The effluent from the first countercurrent separator is then distilled to separate the AlCl_3 from the FeCl_3 and then treated with oxygen to produce Fe_2O_3 and NaCl with the Fe_2O_3 available as a product, the chlorine released being returned to the chlorination loop. Correspondingly, the TiCl_4 and SiCl_4 separated in the second distillation step are oxidized and available as a product, the chlorine being recycled to the chlorinator. If oxidation of the TiCl_4 is handled properly, the resulting TiO_2 has reasonable value as a paint pigment. In the case of the SiO_2 , it can be present in the form of small particles, similar to the TiO_2 , but the market for this product is rather limited. Therefore, if the chlorination were conducted aboard the plantship, it would be necessary to dispose of the NaCl and SiO_2 byproducts at sea. Discharge of these materials at a station 500 m down the cold water pipe, presumably below the thermocline layer, should be a reasonable option for disposal of this inert material.

Fig. 2-24 Alcoa Chloride Process (Assumed Scheme)

Fig. 2-25. Toth Chlorination Process Modified to Produce Aluminum Trichloride

Preliminary calculations suggest that a chlorination plant and the chloride reduction cells could be accommodated on the deck of a 100-MWe OTEC/aluminum plantship. The two chlorination reactors would be about 12 m in outside diameter, with all of the other elements in the flow train of the order of 3 to 5 m in diameter. Having the chlorination equipment and the chloride reduction cell together should offset some of the onboard storage required, and hence need not increase the hull displacement.

2.5.4 Chloride Process Plantship Details

We will assume that within the time that it takes for OTEC plantships to become commercial, both the shore-based production of aluminum chloride and the reduction cells to be used on the plantships will have been demonstrated on a commercial scale, so that the OTEC/plantship concept will not be burdened with process R & D costs, but only with the costs of adapting a developed process to a marine environment.

Referring back to Figure 2-20, aluminum chloride is fed from storage to the reduction cell where it is electrolytically reduced to aluminum and chlorine gas, which is vented from the cells. Any residual AlCl_3 containing compounds such as NaAlCl_4 or KAlCl_4 carried over with the chlorine are recovered as the chlorine is cooled, and the solids are returned to the cells. The cooled chlorine is then compressed, liquefied, and stored for return to the shore base. Following the teachings of Haupin,⁽¹⁹⁾ the electrolyte is reprocessed to remove impurities.

Following the teachings of Haupin⁽¹⁸⁾ and Russell,⁽³⁰⁾ we adopt a voltage drop of 3.3 V/cell at $j_a = 13.2 \text{ kA/m}^2$. If we assume a bipolar cell with an area of 9 m^2 per side, the required current is 123.0 kA. With 0.90 current efficiency, 240 plates will be required to use the 97.5 MWe available after 2% rectification losses and 1/2% transformer losses. The d.c. voltage at the busbar is 793 V. The required 240 bipolar plates would be contained in 20 cell stack assemblies. Assuming a distance of 4.5 m between the cell stack assemblies, the floor area required for the reduction plant is about $47 \text{ m} \times 58 \text{ m}$, or 2735 m^2 , which is considerably less area than required by the other options considered. Because of the small number of cell stacks which must be connected by busbars, the busbar losses are of the order of 1 volt. A busbar configuration is shown in Figure 2-21.

The above conditions lead to an aluminum production rate of 2.48 kg/sec or 78,260 MT/yr for 100 MWe input.

Referring to Figure 2-20, we see that after the heat and AlCl_3 containing compounds have been removed from the chlorine stream, the chlorine must be liquefied. Chlorine liquefaction requires about 0.9 tons of refrigeration per ton; i.e., the heat of vaporization of the Cl_2 is 121 Btu/lbm compared to the 144 Btu/lbm heat of fusion for ice. This will require the equivalent of 861 tons per day of refrigeration capacity. Because of the potential reaction between ammonia and chlorine, freon cooling cycles are usually specified. This cycle will require about 850 horsepower of compressor capacity which is about 635 kw of electrical input. It is assumed that this and other process power required will be derived by waste heat recovery cycles which have the potential for 3 or 4 MW of electrical output in this application.

Aluminum Chloride Plantship

Since nothing is added to or subtracted from the reactants during their processing, the total weight remains the same, they just move from one bin or tank to the other after they have passed through the reduction cell.

For an annual production rate of 78,260 MT, the following quantities are associated with a 7-day operating period, the period for which we assume storage must be provided: AlCl_3 , 7,580 MT ($8,814 \text{ m}^3$); Al, 1,533 MT ($1,167 \text{ m}^3$); and Cl_2 , 6,047 MT ($4,170 \text{ m}^3$).

The AlCl_3 will be stored in three closed, 3000-m^3 silos, (similar in size to those used for alumina). Because AlCl_3 is very hygroscopic, closed, controlled-atmosphere storage containers are required on the support ships carrying the AlCl_3 to the plantship. Transfer to the plantship, and distribution within the plantship will be by dense phase fluidization using dried air or inert gas as the carrier. On-board chlorine storage might be done in standard 90-ton chlorine tanks similar to those used on railroad cars for on-board storage, but since each tank provides only 50 m^3 of storage, a 7-day supply would require about 84 units. Hence it may be appropriate to use larger tanks, say 4-m-diam x 40-m long units. Such tanks will need internal baffles to reduce the free surface effect which might increase platform overturning moment. Another alternative would be to store the chlorine in one 20-m-diam sphere.

To investigate the feasibility of transferring the aluminum particles and AlCl_3 by fluidization, the test setup shown in Figure 2-26 was used. Aluminum or AlCl_3 particles were fed from the hopper into a 0.0254-m-diam (1-in.) flexible line which used nitrogen at about atmospheric pressure as the carrier gas. The apparent density of the AlCl_3 was 1.1 kg/m^3 and the apparent density of the aluminum particles was 1.4 kg/m^3 . The nitrogen flow rate was established, and the material was fed from the hopper into the transfer line. A small vibrator kept the material flowing smoothly from the hopper. Figure 2-27 shows the mass flow rates as functions of the nitrogen superficial velocity. Fluidization of the AlCl_3 started at 2 m/sec, while 5 m/sec is required for the aluminum particles. At the higher flows for the AlCl_3 , it appeared during the tests that gas was flowing back through the pipe at the exit for the feed container, limiting the flow of powder at the source; this may be the reason for the curving over of the AlCl_3 flow data at higher superficial velocities. These tests show that both materials may be readily moved by pneumatic conveyors.

Figures 2-28 and 2-29 are artist's conceptions of 100-MWe (net) AlCl_3 plantships on barge-type and semisubmersible hulls where:

1. Total number of cell stack assemblies = 20 @ 200 MT each.
2. Storage = 20,000 L Tons.
3. Materials cost = concrete @ $\$750/\text{yd}^2$; steel @ $\$2,000/\text{ton}$.
4. Platform stationkeeping = grazing.
5. Crew = 100 men.
6. Cold water pipe - steel in section, hinged joint at the platform, semi-buoyant.

Fig. 2-26 Test Setup for Measuring Parameters for Pneumatic Transport of Aluminum Chloride Powder and Centrifugally Cast Aluminum Particles

Fig. 2-27 Pneumatic transport test data for aluminum chloride powder and centrifugally cast aluminum metal particles

Fig. 2-28 Aluminum OTEC Plantship - 100 MWe (NET) Rectangular Barge
500 x 200 x 120

Fig. 2-29 Aluminum OTEC Plantship -- 100 MWe (NET) Semisubmersible
440 x 240 x 192

The characteristics of each plantship are given in Table 2-4.

The barge-type hull cost is estimated to be \$73M, compared to \$116M for the semisubmersible hull.

A 1/200th scale model of the plantship with a semisubmersible hull was constructed by TRW (Figure 2-30).

Three options were examined as the transport vessel for bringing the aluminum chloride (AlCl_3) to the plantship and returning the aluminum and the chlorine to the support base.

- 1) A dedicated product carrier (Figure 2-31) incorporating a screw-type conveyor and self-unloading system which eliminates the need for special handling equipment aboard the offshore platform;
- 2) A Seabee products carrier (Figure 2-32) incorporating a small, shallow-draft, open-decked vessel similar in concept to a Navy LST, with a ballast system and bow doors for loading and unloading barges; and
- 3) A tug-barge combination (Figure 2-33) which would use two or more dedicated barges incorporating the storage and unloading features shown in the dedicated product carrier. Under this concept, some of the onsite inventory could be on a storage barge tied up alongside the plantship, instead of having it all on the platform. The propulsion unit would then be used shuttling the barges back and forth between the shore base and the platform(s).

TABLE 2-4 ALUMINUM CHLORIDE 100 MW_e REDUCTION PLANTSHIP COMPARISONS

	HULL TYPE		
	SEMISUBMERSIBLE		BARGE
	LOWER HULL	UPPER HULL	
LENGTH FT.	440	440	550
BREADTH FT.	240	240	200
DEPTH FT.	82	30	120
COLUMNS FT.	(4) 115 x 60 x 80 (2) 80 x 60 x 80		
DISPLACEMENT LT		303,740	
BARE HULL WT. LT		198,494	106,358
DRAFT		65.8	42.3
HULL COST \$ x 10 ⁶		115.89	73.42

Fig. 2-31 Dedicated Products Carrier Ship

Fig. 2-32 Sea Barge Carrier

Fig. 2-33 Seabee Barge Carrier

Fig. 2-34 Comparison of 100 MWe OTEC platform to the space required for production of about 700,000 MT/yr of aluminum by conventional Hall process, drained cathode Hall process, and aluminum chloride reduction process.

2.6 Plantship Configuration Comparisons

In Section 2.2, we described a plantship based on conventional Hall cell technology including a design anode current density of 7.0 kA/m^2 . This plantship was 900 ft long and 440 ft wide with a displacement of 507,000 tons. In Sections 2.3 and 2.4 we developed tentative specifications for a drained-cathode Hall cell plantship and an aluminum chloride reduction plantship, respectively. The characteristics of these plantships are compared in Table 2-5 with the conventional Hall cell plant design normalized to 100 MWe and hence using only 148 cells (in place of 180 cells postulated in Section 2.2) and producing 60,000 MT/yr. For the drained-cathode plant, the corresponding number of cells is 108, with the production increased to 63,640 MT/yr.

In the aluminum chloride reduction plant, the current densities are high, and there are a number of bipolar plates in each cell stack assembly, so the number of equivalent cells, is reduced to twenty while the output is increased to 78,260 MT/yr and the plantship hull is sharply reduced in size. Figure 2-34 compares the areas required for roughly the same annual production from each option. The natural size of a 100 MWe OTEC power plant is given in References 31 and 32 for a circular spar platform as about 300 feet diameter, which has an area of about $70,000 \text{ ft}^2$, or $6,500 \text{ m}^2$, which is equivalent to a square about 80 m on a side. This area is also shown in Figure 2-34 for comparison. As can be seen, the aluminum chloride reduction plant fits comfortably on the deck of an OTEC floating power plant, while the drained-cathode reduction plant would require some increase in hull size.

Table 2-5. SUMMARY OF REDUCTION PROCESS PLANTSHIPS

VARIABLE	UNITS	HALL PROCESS	DRAINED CATHODE HALL PROCESS	CHLORIDE PROCESS
Reactants		$\text{Al}_2\text{O}_3 + \text{Carbon}$	$\text{Al}_2\text{O}_3 + \text{Carbon}$	AlCl_3
Products		$\text{Al}(l), \text{CO}, \text{CO}_2, \text{HF}$	$\text{Al}(l), \text{CO}, \text{CO}_2, \text{HF}$	$\text{Al}(l), \text{Cl}_2(g)$
Reaction Temperature	C	945 ± 5	945 ± 5	700
Coulombic Efficiency		0.89	0.90	0.90
Anode Current Density	kA/m^2	7.0	14.0	13.2
Voltage/Cell	V	4.25	4.06	3.3
Anode Area/Cell	m^2	15.6	15.6	9×12
Floor Area/Cell	m^2	114	78	81
Energy Requirement	kWhr/kg Al	14.2	13.43	10.91
Power Input	MW	100	100	100
Production Rate	kg/sec	1.9	2.0	2.48
Production Rate	MT/yr	60,000	63,640	78,260
Number of Cells		148	108	$240/12 = 20$
Deck Area Required	m^2	16,872	8,424	1,620
Power Supply Voltage	Vdc	630	440	793
Power Supply Current	kA	155	218	123

Previous investigators who have examined the use of OTEC systems to produce aluminum^(1,2) and other commodities such as ammonia,^(1,34-36) chlorine-caustic soda, have usually used a set of economic assumptions which, while pertinent to the screening function that these studies were performing, were not very useful to the aluminum industry. Traditionally, the location of alumina reduction plants or "smelters" has been made on the basis of the cost of electricity which was available, since aluminum production then required about 15.4 kWh/kg. For this reason, primary aluminum smelters historically have been located in regions of surplus or abundant energy. Virtually all U.S. capacity is located in the Pacific Northwest, the Gulf Coast, the TVA service area, the Ohio River Basin, and along the St. Lawrence Seaway, as shown in Figure 1-5. During the period when most of these plants were built, electric power was available from the Federal hydroelectric projects at a cost of about 2.5 mills/kWh. Along the Gulf Coast where natural gas was plentiful, gas was available at costs between \$0.15 and \$0.20 per 1000 ft³, which when used in power systems having a heat rate of 12,000 BTU/kWh made possible the generation of electricity from fossil fuels at costs comparable to the available hydroelectric power. It is against this history of location decisions and the number of undeveloped hydroelectric sites which are still available around the world that we must present the OTEC option.

Integrated Production Chain--Because of the integrated nature of the industry, a decision to expand the primary production of aluminum carries with it the decision that some place the production of alumina must be increased to provide the alumina feedstock for the reduction plant, that somewhere there must be an increase in electrode carbon production, an increase in power generation capacity (to provide the electricity required by the reduction process), and an increase in fabrication capacity to turn the products of the reduction plant into semifinished products such as plate, strip, wire, rod, or bar, etc., which are then fabricated into finished products.

The cost of the product will depend upon the costs all along this chain. For the present analysis, we will limit our consideration to those production facilities and processes which are required to produce aluminum ingots of 99.5% purity and will not consider processing of the ingots into semifinished products. However there is no free market price for alumina nor for aluminum trichloride produced from bauxite or clays in the quantities required for the production of several hundred thousand tons of aluminum per year. Thus, we will include in our OTEC-aluminum model the capital and operating costs of all of the facilities which are required to take the input raw materials and convert them to aluminum ingots.

This type of model should present OTEC power systems in their best light. It will allow, on a case-by-case basis, the determination whether an OTEC power system or a conventional power source would provide the highest rate of return on investment (ROI) for this increase in capacity. It is important that the OTEC options be framed in terms of potential ROI, which is the most commonly used decision making criterion used in the industry. If we

were to address OTEC as a power system capable of delivering electricity at a cost of 50 to 70 mills/kWh it would never be seriously considered by industry because the historical perception is that electricity used to produce aluminum has to cost less than 15 mills/kWh to be competitive, and if it can continue to be had for 10/mills/kWh at present hydroelectric sites, so much the better.

The fact that the cost of OTEC energy, (like hydroelectric power) is relatively free from inflation and the other factors which affect the world's energy supplies, is not readily perceived by many. It is only through a detailed cash flow analysis over the life of the project that the ROI of a conventional option can be compared with another option, such as an OTEC energy source. Once the economic superiority of one option over the other is established in this manner, then the decision makers must judge whether (1) the technology which has been assumed in the competing options can be achieved (i.e., how well OTEC will work), and (2) that the quantities produced can be sold at the assumed sales price.

Predicted Aluminum Sales Price--The U.S. Bureau of Mines has projected the U.S. aluminum growth from 1976 to 1985 at 7.9% annually, which is less than the growth of the past three decades but more than the projected growth of GNP. After 1985, the growth may slow to 4-1/2% greater than the real growth in GNP. Continuation of the increase in demand at rates of this magnitude will insure that there is a market for the OTEC-derived aluminum. The world selling price of aluminum ingots has for a number of years correlated well with the U.S. Whole Price Index, WPI. Therefore, the price for which OTEC-produced aluminum can be sold can be predicted reasonably well if the WPI can be forecast well.

Annual Load Factor--Since the smelting of aluminum is an electrochemical process for which production is directly related to the number of coulombs passed through the system, and the operating temperature is maintained at a constant level by the ohmic losses associated with the current passed through the system, the Hall process is operated at as close to constant current as is possible throughout the entire operating period of the plant which may be 30 to 40 years, i.e., the potline is never shut down for maintenance. Instead, individual cells are removed for rework on about a four-year cycle. This implies constant power input for 24 hours a day, 365.25 days per year. In conventional power plant economic analysis, the procedure usually is to assume some sort of an annual load factor based on operating experience, e.g., 0.55 for nuclear plants 0.65 for coal-fired plants, or 0.70 for gas-fired plants. These factors result in part from seasonal variations in demand for electricity. However, for an OTEC-aluminum plant it will be necessary for the smelting plant for the plant availability to be very high. In Section 2.3, we have addressed the necessity for having standby power sources to insure that 100% of the nameplate rating would be available at all times and in Section 2.1 have addressed several scenarios for estimating the amount of fossil fuel required. In our economic models, the extra investment in gas turbines and the extra hull cost for storage, etc., appear in the capital cost. The fact that we have included these systems in the design will let us use an annual load factor of 1.00, or some number very close to it.

Levelized Busbar Cost of Electricity (LBCE)--While the LBCE is meaningful in evaluating and ranking various power plant configuration options, it may not present the true potential of a given power system when inflation rates are high as they have been in recent years. The LBCE is determined by summing all capital, operating, and maintenance costs over the lifetime of the project and then dividing the sum by the total units of electricity produced. The LBCE is frequently used by the electric utility industry in ranking their choices for system expansion.

Discounted Cash Flow (DCF) Analysis--The use of DCF for ranking investment opportunities is different. Because some of the costs and incomes might not be constant over the life of the project, DCF analysis is preferred by many financial analysts. For industrial projects, it is assumed that a plant is built to produce a product which is sold in a market with a specified profit margin. This is analyzed by examining the cash flow, i.e., investment, profit, depreciation, taxes, etc., and then finding the discount rate which yields a zero net present value for the project. This discount rate is called the internal rate of return. The discounting applies not only to the profits which occur in the future, but also to future costs which may arise.

The procedure to be used is to discount the cash flow to find the present value of each year of the cash flow. The present value, P_n , of the cash flow, C_n , in the n th year is $P_n = C_n (1 + i)^{-n}$, where i is the interest rate. The rate of return is determined by finding the interest rate, $i = d$, which yields zero for the sum of the yearly "present values," i.e., net present value over the life of the project.

3.1 Economic Model Assumptions

Project Capital Structure--As shown in Figure 3-1, the invested capital per dollar of sales from the aluminum industry is almost twice as high as it is for the manufacturing industries. In addition, as shown in Figure 3-1, the aluminum industry has a high debt-to-equity ratio. As shown in Figure 3-2, the aluminum industry's ROI is lower than the 16% realized by all industry in that year. These characteristics restrict the industry's ability to proceed with many attractive capital opportunities and to expand primary production.

Because of the existing high debt-to-equity ratios, the only way that expansion projects of the magnitude that we will address in subsequent sections can be financed is by going to "project" financing, which does not appear on the corporate balance sheet but is covered as a footnote on the financial report. A project may typically be carried out by two or three participating members of the industry who put up the initial capital, say 20% of the total cost of the project, and then agree to firm contracts with the project to take or pay for a certain percentage of the project's output product. Most of the funds are raised from investment bankers who hold a chattel mortgage on the facilities and inventory of the project, backed by the take or pay purchase guarantees of the industry participants. Because of the small amount of equity or investment in such a venture by the participants, it is also appropriate to determine the rate of return on assets of any such project, because this is what will determine whether the project can be financed by the investment community.

Fig. 3-1 CAPITAL INTENSITY OF THE ALUMINUM INDUSTRY
Average 1970-79

Fig. 3-2

Source:
Aluminum Association

*Invested Capital: Total debt plus shareholders equity
Source: FTC data; Standard & Poors, Alcoa, Kaiser, Reynolds annual reports

Taxes--For our baseline example, where we have assumed a Bayer plant and Hall plant located on the U.S. Gulf Coast, the tax question is straightforward. We have assumed the U.S. corporate income tax rate of 46%. We have also assumed that the present investment tax credit (ITC) equivalent to 10% of the cost of the production facilities, less land, can be applied against 70% of the income tax liabilities generated by the project profits from the first through the seventh years of operation. Local taxes are assumed as part of the operating costs and are based on a 1% per year assessment on the initial capital investment, and are considered to escalate with the GNP deflator.

For the cases where OTEC energy is used, we have assumed that an additional 15% solar energy ITC, specified in the "Windfall Profits Tax" Act PL 96-223, will be available for those portions of the project which are on the OTEC platform, or part of the afloat support system. We have assumed that the 15% solar energy ITC will be extended by Congress beyond 1985, that it will be extended beyond the first five installations and the two sites provided for in the original legislation, and that the provision which allows it to be applied against the total federal tax liability in place of the normal 70% limitation would also be extended. We have assumed that all portions of the system that are on land will enjoy only to the basic 10% ITC.

The ITC can be taken against the project, or against the parent company. Our analyses show that taking the ITC against projects of the type we are considering spreads them over the seven year period is allowed, so that for the high discount rates of interest, the investment ITC has little apparent effect, say about 1%, on the project's indicated rate of return. Being able to take the ITC against the tax liability of the parent company may allow this credit to be taken sooner in the project lifetime, and hence it has a higher present value. However, aluminum producers, as shown in Figure 3-2, have low return on invested capital and may have difficulty in generating adequate profits to fully utilize the ITC, especially during the first few years of project operation. For this reason, it may be desirable to have some form of "leveraged leasing" for those facilities which are eligible for the additional solar energy ITC so that this ITC can be passed through to other parties who can use the cash flow against their tax liabilities.

In our analyses we have calculated the rate of return on the basis of both (a) the ITC limited to the specific project; and, (b) the ITC being in an unconstrained ownership structure with sufficient tax liability such that all of the ITC could be taken in the first year. For the projects examined, it was necessary to assume a \$3 billion income tax liability, i.e., profits of roughly \$6 billion, to fully utilize the ITC in the first year of the project.

Our financial model uses the following assumptions for depreciation:

Table 3-1 Depreciation Schedule

Element	Depreciation Life	Scrap Value
	Yrs	%
Production Facilities	11	10
Office Facilities	25	10
Infrastructure Facilities	20	10

United States corporation income taxes--The U.S. corporate tax rate is 46%, with a 10% ITC which can be for a period of 7 years to offset 70% of the tax liability, and a 15% solar energy ITC which can be used to offset any remaining tax liability during the seven year period.

Puerto Rico corporate income taxes--The maximum income tax rate is 45%. Under certain conditions, which would apply to the project which we are considering, the manufacture of a product, the income is exempt from taxes during the first five years, 75% is exempted the next five years, 65% is exempt during the next five years, 55% is exempt during the next five years, and 50% is exempt in the last five years. The tax rate then returns to 45%. This results in a corporate income tax rate for the first five years, 11.25% for the next 5 years, 15.75% for the next five years, 20.25% for the next 5 years, 22.5% for the next 5 years, then returning to the basic 45% corporate tax rate. There is no investment tax and no solar energy ITC. There is a withholding tax of 10% if profits are repatriated from Puerto Rico on a current basis.

Virgin Islands corporate income taxes--The rate is 46%, equivalent to the U. S. corporate tax rate, but qualified Virgin Islands corporations are refunded 90% of their taxes for the first 10 years, or 15 years for certain locations, as well as granted certain other reliefs from local taxes and import duties. ITC is applicable (from the U.S. Tax Code), but is not important.

Guam corporate income taxes--The U.S. Tax Code applies, but the Guam Economic Development Authority may authorize a 75% tax forgiveness for a period of up to 15 years.

Philippine Islands income tax--We assume that a Philippine corporation would be formed to operate the OTEC plant and the aluminum production facilities. The corporate income tax rate is about 30% for the first eight or nine years and rise to 40% thereafter.

Financing--We have assumed in our economic models that the projects being addressed would have two separate financing structures. It is assumed that the OTEC plantship and all of its onboard production equipment and water-borne transport systems would qualify for 87.5% loan guarantees under Title XI of the Maritime Administration Act. Because of the U.S. Government loan guarantee, it is assumed that this loan would be at 1% less than the long term interest rates. It is assumed that either 80% or 30% of the non-floating parts of the project would be financed by loans at the long term interest rate, which is equal to cost of money plus the embedded inflation. We have assumed the long term interest rate at 12%, that the loan would be repaid within 20 years, and that the short term interest rate, to cover money borrowed during construction, is 10%. It is assumed that the investment during construction follows the traditional "S" curve. We further have assumed that the project can be completed in 3 years and that during the fourth year production will be at 70% of the nameplate rating.

We have assumed that the initial working capital required is equal to 4 months worth of sales. The return of working capital at the end of the project is shown as a positive cash flow at that time.

Sales Price--We have assumed in all of the analyses that follow that the sales price F.O.B. in the world market of the 99.5% pure aluminum ingots produced would be \$1.59/kg (\$0.72/lbm), escalated by the GNP deflator from the mid-1980 price.

The cost structure, in addition to the above elements, includes working capital costs, land costs, permit cost, startup and pre-operation costs.

The discounted cash flow model used calculates interest and escalation during construction. These are added to the initial capital elements for the calculation of taxes, rate of return, etc. The calculation covers the cash flow over the 33 year life of a Bayer-Hall production complex on the U.S. Gulf Coast, which is supplied with electricity at \$0.015/ kWhr. Details of the estimated capital and operating cost of the baseline are contained in Case A.1.1 of Appendix A.

It may be noted that the 46% corporate tax rate, in the U.S., bears heavily on the ROI of such a project. There are a number of opportunities to operate OTEC systems in near equatorial areas where a different tax structure might be applied. In this case, the OTEC-produced aluminum may be subject to import duties when entering the U.S., and secondary issues might arise such as the effects of operating under a flag of convenience, etc.

3.1.1 Example of Effect of Tax Rates on ROI

Because of the capital intensity of the OTEC power system, any change in the tax policies which favors the retention or formation of capital, e.g., lower corporate income tax rates, speeded up depreciation, etc., will make the ROI on projects using OTEC energy systems appear more favorable with respect to alternative methods of achieving the same increases in production which require fuels. As an example, let us examine the rate of return as a function of the sales price of electricity for an OTEC power system supplying a Caribbean island. We will consider U.S. income taxes with the two ITC options, the Puerto Rico income tax structure; and the Virgin Islands tax structure.

For this example, we will assume that the OTEC plant is to produce 40 MWe and as a first of a kind demonstration unit it will cost \$270 million, installed; that the operation and maintenance costs for the OTEC plant will be 6 mils/kWh and will escalate with the projected 7% GNP deflator; that 30% of the project is financed, for 20 years at 12%, and that will take three years to construct.

Results--Figure 3-3 shows the projected after tax rates of return for the foregoing cases. Because of the different ΔT 's, which would change the capital investment, the ROI for plants built on Guam or the Philippine Islands is not shown. It is seen that U. S. corporate taxes, with the tax liability limited to the project, gives the lowest rate of return for any sales price of electricity. Assuming that the income tax liability for a large corporation (assumed \$3 billion) could be applied, so the the total ITC (25%) can be used in the first year of the project, profitability is indicated to increase by about 4% for all sales prices of electricity. Since the present sales price of electricity on Puerto Rico, Guam, and the

Virgin Islands is about ten cents per kWh, pass through of the ITC can result in a 40% increase in the apparent profitability of the project under 1980 U.S. corporate tax laws.

Application of the Virgin Island or Puerto Rico corporate tax structures to the project yield rates of return which are 15% and 25% higher, respectively, than the U.S. case where the tax liability is limited to the project for our assumed 1980 sales price of \$0.10/kWh.

We should note that the indicated high capital cost for the project, \$6750/kWh, is for a first commercial-scale OTEC demonstration project. As we will see in the next section, Table 3-9, the estimated cost per kilowatt for $\Delta T = 22^\circ\text{C}$ in a mature technology is about \$2170/kW, or about 32% of this assumed first plant price. If the OTEC system were presently available for \$2170/kW, the indicated rate of return for a \$0.10/kWh sales price would be about 35% or greater, regardless of the tax structure assumed.

Figure 3-3 Rate of Return on Investment for 40 MWe OTEC Plant for Various Corporate Income Tax Rates

3.2 Cost Data for Economic Models

The scope of the present study was not adequate to allow conceptual designs to be prepared for any of the options to be considered. Detailed facility operating costs are closely held data within the operating organizations to prevent disclosure to potential competitors. Therefore, we decided to use estimates from the open literature, notably those published by A. D. Little in 1976,⁽³⁶⁾ and those published by Argonne National Laboratory (prepared by A. D. Little, Inc.) in 1979.⁽³⁷⁾ The A. D. Little report gave estimates for capital costs and breakdowns of projected production costs for the Bayer process, the Hall process, the Hall process with drained cathodes, the chloride reduction process, the Toth process, and the combination of a chlorination and chloride reduction process. For each of these cases, a capital cost estimate was given along with a breakdown of the projected production cost for each of these configurations. In addition, a cost breakdown by components was given for a Hall process reduction plant. These estimates were used as baselines for adjusting capital costs and operating costs (using the Chemical Engineering Construction Cost Index which is shown in Figure 3-4) to mid-1980, and as a starting point for configurations which were not considered in those studies.

Figure 3-4 Chemical Engineering Plant Cost Index from Chemical Engineering Magazine, August 1980

3.2.1 Facilities for Producing Alumina or Aluminum Chloride

Bayer Process--Table 3-2 provides a production cost estimate for a Bayer process plant on the U.S. Gulf Coast, in the format of Reference 36 but the quantities are changed from units consumed per net short ton of alumina, to units consumed per net short ton of aluminum. We have updated the unit costs for variable inputs to 1980 using recent quotations or, when not available, from 1975 to 1980 with a 7% annual GNP deflator. The wage rates are plant averages based on mid-1980 contract settlements.

We may note that our economic model calculates depreciation on an accelerated 11 year rate, and determines the return on investment after taxes. Therefore, this type of information shown in Table 3-2 and those that follow is not used in the financial analysis, but is presented here only to preserve the format presented in Reference 36.

As will be seen in the detailed cost inputs given in Appendix A, the manhour costs were combined with supervision costs to reduce the number of inputs. The basic rate was multiplied by 1.15 to account for supervisory labor and by 1.32 to account for fringe benefits. After all of the burdened labor costs were added together, the plant overhead of 45% was applied. This is equivalent to the application of 60% overhead to the unburdened wages.

The average purchased electricity costs in the U.S. Gulf Coast region were estimated to be \$0.03/kWhr in 1980, and it was estimated that natural gas would be available at \$4.00/million BTU. As will be explained in Section 3.3.1, it is estimated that the cost of electricity will increase more rapidly than the GNP deflator.

The capital cost data for a Bayer process plant is given in Reference 36 for an annual output of 700,000 t/yr, and in Reference 38 for Bayer process plants with annual outputs of 600,000, 800,000, 1,000,000, and 1,200,000 MT/yr. Reference 38 concludes that the capital costs of the Bayer process plant scale as the throughput to the 0.7 power.

Chlorination--For chlorination, we consider the Toth process which was discussed in Section 2.4.3. Table 3-3 presents data from Reference 36 on the estimated capital costs and production costs for a Toth process plant producing 1,800,000 t/yr of $AlCl_3$, to produce 362,700 t/yr of aluminum, which is equivalent to the 700,000 t/yr Bayer plant in Table 3-2. We have modified the quantity of oxygen to be used to account for the fact that the product is $AlCl_3$ rather than Bayer grade alumina which was assumed in Reference 36.

Since the estimated capital cost of the chlorination plant is only slightly less than that of a Bayer plant of equivalent output, we have assumed that the chlorination plant capital costs would scale as the aluminum content throughput to the 0.7 power. Data on the capital costs and production costs for the Alcoa chlorination process as a stand-alone facility are not available in the open literature.

TABLE 3-2

ESTIMATED PRODUCTION COSTS IN "NEW" BAYER ALUMINA PLANTS, 1980

Product: <u>Alumina</u>	Process: <u>Bayer</u>	Location: <u>Texas</u>		
Annual Capacity: <u>7000,000 Short Tons</u>	Capital Investment: <u>\$406,800,000</u>	Annual Production _____		
	Units Used In Costing Or Annual Cost Basis	\$/Unit	Units Consumed Per Short Ton Of Aluminum	\$Per Short Ton Of Aluminum
VARIABLE COST				
Raw Materials				
. Bauxite	Short Ton	33.80	4.632	156.56
. Limestone	Short Ton	7.35	0.257	1.89
. Soda Ash	Short Ton	105.00	0.145	15.20
Energy				
. Purchased Fuel (A)				
- Fuel Oil or Gas	10 ⁶ BTU	4.00	22.47	89.86
. Electric Power Purchased	kWh	0.030	530.75	15.92
. Misc.	—	—	—	—
Water				
. Process	10 ³ GAL	0.50	3.86	1.93
. Cooling	10 ³ GAL	0.05	5.31	0.265
Direct Operating Labor (Wages)	Man-Hr	9.54	1.70	16.20
Direct Supervisory Wages	15% Op. Lbr.			2.43
Maintenance Labor (Wages)	Man-Hr	9.54	0.80	14.73
Maintenance Supervision (Wages)	15% Mnt. Lbr.			2.21
Maintenance Materials & Supplies	1.5% of CI			16.82
Labor Overhead	32% of Wages			11.38
Misc. Variable Costs/Credits				
. Starch	Short Ton	260.00	0.0116	3.01
TOTAL VARIABLE COSTS				408.78
FIXED COSTS				
Plant Overhead	60% of Wags			21.34
Local Taxes and Insurance	2% of CI			22.43
Depreciation	7.1% of CI			79.63
TOTAL PRODUCTION COSTS				532.18
Return on Investment (Pretax)	20% o CI			224.30
Pollution Control				3.93
TOTAL				760.41

(A) E.G., Misc. Chemicals, Catalysts, Supplies, Services.

TABLE 3-3

ESTIMATED PRODUCTION COSTS FOR NEW ALUMINA PLANT, 1980
(CLAY CHLORINATION - TOTH)

Product: Aluminum Chloride Process: Clay Chlorination: Toth Location: Texas or Georgia.
 Annual Capacity: 1,800,000 Short Tons Capital Investment: \$337,930,000 Annual Production: _____
 (Equivalent to 362,700 Short Tons of Aluminum)

	Units Used In Costing Or Annual Cost Basis	\$/Unit	Units Consumed Per Short Tons Of Aluminum	\$ Per Short Ton Of Aluminum
VARIABLE COSTS				
Raw Materials				
. Clay (Kaolin)	Short Ton	10.00	5.79	57.90
. Chlorine	Short Ton	150.00	0.077	11.58
. Oxygen	Short Ton	20.00	2.53	50.57
Byproduct Credits (Crude TlO_2)	Short Ton			-54.50
Energy				
. Purchased Fuel				
- Coal	10^6 BTU	1.50	16.31	24.46
- Coke	Short Ton	50.00	1.235	61.76
. Electric Power Purchased	kWh	0.03	646.70	19.28
. Miscellaneous	-	-	-	-
Water				
. Process	10^3	0.70	1.544	1.08
. Cooling	10^3	0.07	39.08	2.74
Direct Operating Labor (Wages)	Man-HR	9.54	1.39	13.26
Direct Supervisory Wages	15% Op. Lbr.			1.99
Maintenance Labor (Wages)	Man-HR	9.91	2.03	20.08
Maintenance Supervision (Wages)	15% Mnt. Lbr.			3.01
Maintenance Materials	2% of CI			18.63
Labor Overhead	32% of Wages			12.27
Misc. Variable Costs/Credits				
. Other Operating Supplies				<u>16.50</u>
TOTAL VARIABLE COSTS				<u>260.61</u>
FIXED COSTS				
Plant Overhead	60% of Wages			23.00
Local Taxes and Insurance	2% of CI			18.63
Depreciation	7.1% of CI			<u>66.13</u>
TOTAL PRODUCTION COSTS				<u>368.37</u>
Return on Investment (Pretax)	20% of CI			186.30
Pollution Control				<u>30.28</u>
TOTAL				<u>584.95</u>

3.2.2 Reduction Plants

Hall Process--Table 3-4 provides an estimated capital cost breakdown for a new prebaked anode aluminum reduction plant of 145,190 MT/yr capacity to be built in the United States in mid 1980 dollars. This estimate from Reference 39 has been updated using the chemical engineering plant cost index, Figure 3-4. This table is important because when some of the OTEC options are being considered, certain functions will be performed at the shore base and some functions will be performed on the OTEC platform. This table allows the costs to be allocated between the two locations, or to be adjusted as parameters such as anode current density are changed. It is assumed that the capital cost of most of the production facilities at the reduction plant will scale directly as the aluminum mass throughput since it is basically a coulombic process. However, the storage and support facilities are scaled as the throughput to the 0.7 power. Examples of the use of Table 3-4 are given in Appendix A.

The estimated production costs in a new Hall process reduction plant are given in Table 3-5. Again, we have updated the costs of the input quantities. It is assumed that this plant would incorporate the best available technology and would consume 14.52 kWh/kg of a.c. electrical power for the potline, and 0.67 kWh/kg of a.c. for plant auxiliaries making the total requirement 15.19 kWh/kg of aluminum.

When considering the shore-based, drained-cathode Hall cell plants, we assumed that the plant would be designed with an anode current density of 7 kA/m². For production of 160,000 t/yr, the reduction plant would have 500 cells in place of the 360 cells assumed as the basis for the prebaked Hall plant cell capital cost estimate in Table 3-4. Table 3-6 from Reference 36 gives the capital cost and production cost estimates (updated to mid-1980) for the drained-cathode cell plant using titanium diboride cathodes.

Chloride Process--Table 3-7 presents estimated production costs for a combined Toth chlorination plant and an aluminum chloride reduction plant from Reference 36. Again, we have updated the capital costs using Figure 3-4 and updated the unit costs to 1980. In our economic analysis we take credit for the TiO₂ and Fe₂O₃ produced as part of the sales price of the products and do not treat it as a byproduct credit as shown in Table 3-7.

For completeness and comparison, the estimated production costs for what is called the "Alcoa Chloride Process" in Reference 36, are given in Table 3-8, which has been updated from by the use of Figure 3-4 and current prices. This process postulates the use of the chlorination process shown in Figure 2-24 which uses No. 6 fuel oil as the carbon source to produce the AlCl₃, and the aluminum chloride reduction process we have previously discussed. In our analysis of Case F3 in Appendix B, we neglect the credit for HCl from this process.

Since neither the Toth chlorination process, the Alcoa chlorination process, nor the chloride reduction process has been operated in commercial practice, these estimated costs are of lower confidence level than those for Hall process.

TABLE 3-4

ESTIMATED CAPITAL COST BREAKDOWN FOR A NEW PREBAKED
ALUMINUM REDUCTION PLANT IN THE UNITED STATES

Capacity: 160,000 Short Tons/Year or 145,000 MT/Year

Components	Cost, \$ M (1980)
Alumina and Carbon Storage	9.7
Mobile Equipment	1.5
Carbon Paste Plant	7.1
Green Carbon Plant	27.2
Carbon Baking Plant	35.4
Carbon Rodding Plant	20.5
Substation	4.5
Retifiers	25.4
Potlines	50.7
Busbars	32.8
Structures and Ventilation	62.7
Metal Casting	23.1
Utilities excluding Power Plant	17.9
Support Facilities and Pollution Control	<u>56.7</u>
TOTAL	<u>375.2</u>

TABLE 3-5

ESTIMATED PRODUCTION COSTS IN NEW ALUMINUM PLANTS, 1980
(HALL PROCESS)

Product: Aluminum Process: Hall Location: Gulf Coast
 Annual Capacity: 160,000 Short Tons Capital Investment: \$375,180,000 Annual Production: 160,000 Tons

	Units Used In Costing Or Annual Cost Basis	\$/Unit	Units Consumed Per Short Tons Of Aluminum	\$ Per Short Ton Of Aluminum
VARIABLE COSTS				
Raw Materials				
. Bayer Alumina	Short Ton	394.00	1.93	760.41
. Cryolite	Short Ton	493.90	0.035	17.29
. Aluminum Fluoride	Short Ton	514.50	0.02	10.29
Energy				
. Purchased Fuel				
- Natural Gas	10 ⁶ BTU	4.00	6.60	26.40
. Calcined Coke	Short Ton	120.00	0.52	62.40
. Pitch	Short Ton	103.00	0.15	15.45
. Electric Power Purchased	AC kWh	0.03	13,780.00	413.40
. Miscellaneous	-	-	-	-
Water				
. Process				
. Cooling				
Direct Operating Labor (Wages)	Man-HR	9.54	3.50	33.39
Direct Supervisory Wages	15% Op. Lbr.			5.01
Maintenance Labor (Wages)	Man-HR	9.54	4.50	42.93
Maintenance Supervision (Wages)	15% Mnt. Lbr			6.46
Maintenance Materials	2.5%			58.62
Labor Overhead	32% of Wages			28.08
Miscellaneous Variable Costs/Credits				
TOTAL VARIABLE COSTS				<u>1,480.11</u>
FIXED COSTS				
Plant Overhead	60% of Wages			52.66
Local Taxes and Insurance	2% of CI			46.90
Depreciation	7.1% of CI			<u>166.48</u>
TOTAL PRODUCTION COSTS				<u>1,746.15</u>
Return of Investment (Pretax)	20% of CI			469.00
Pollution Control				63.92
TOTAL				<u>2,279.97</u>

TABLE 3-6

ESTIMATED PRODUCTION COSTS IN NEW ALUMINUM PLANTS, 1980
(HALL PROCESS WITH DRAINED CATHODES)

Product: <u>Aluminum</u>	Process: <u>Hall (Drained Cathodes)</u>	Location: <u>Gulf Coast</u>
Annual Capacity: <u>160,000 Short Tons</u>	Capital Investment: <u>\$443,046,000</u>	Annual Production: <u>160,000 Tons</u>

	Units Used In Costing Or Annual Cost Basis	\$/Unit	Units Consumed Per Short Tons Of Aluminum	\$ Per Short Ton Of Aluminum
VARIABLE COSTS				
Raw Materials				
. Bayer Alumina	Short Ton	394.00	1.93	760.41
. Cryolite	Short Ton	493.90	0.035	17.29
. Aluminum Fluoride	Short Ton	514.50	0.02	10.29
Energy				
. Purchased Fuel				
- Natural Gas	10 ⁶ BTU	4.00	6.60	26.40
. Calcined Coke	Short Ton	120.00	0.52	62.40
. Pitch	Short Ton	103.00	0.15	15.45
. Electric Power Purchased	AC kWh	0.03	12,648	379.44
. Miscellaneous	-	-	-	-
Water				
. Process				
. Cooling				
Direct Operating Labor (Wages)	Man-HR	9.54	3.50	33.39
Direct Supervisory Wages	15% Op. Lbr.			5.01
Maintenance Labor (Wages)	Man-HR	9.54	4.50	42.93
Maintenance Supervision (Wages)	15% Mnt. Lbr			6.46
Maintenance Materials	2.5% of CI			69.23
Labor Overhead	32% of Wages			28.08
Miscellaneous Variable Costs/Credits				
TOTAL VARIABLE COSTS				<u>1,456.76</u>
FIXED COSTS				
Plant Overhead	60% of Wages			52.66
Local Taxes and Insurance	2% of CI			55.38
Depreciation	7.1% of CI			<u>196.60</u>
TOTAL PRODUCTION COSTS				<u>1,706.02</u>
Return of Investment (Pretax)	20% of CI			553.81
Pollution Control				63.92
TOTAL				2,323.75

TABLE 3-7

ESTIMATED PRODUCTION COSTS FOR NEW ALUMINUM PLANT, 1980
(COMBINATION OF TOTH ALUMINA AND CHLORIDE REDUCTION PROCESS)

Product: <u>Aluminum</u>	Process: <u>Toth AlCl₃ Electrolysis</u>	Location: <u>Georgia</u>
Annual Capacity: <u>160,000 Short Tons</u>	Capital Investment: <u>\$430,040,000</u>	Annual Production: _____

	Units Used In Costing Or Annual Cost Basis	\$/Unit	Units Consumed Per Short Tons Of Aluminum	\$ Per Short Ton Of Aluminum
VARIABLE COSTS				
Raw Materials				
. Clay (Kaolin)	Short Ton	10.00	5.79	57.90
. Chlorine	Short Ton	150.00	0.08	12.00
. Oxygen	Short Ton	20.00	1.47	29.40
. NaCl	Short Ton	30.00	0.001	0.03
. LiCl	Short Ton	2,000.00	2.00	
Byproduct Credits (Crude TiO ₂)	Short Ton	332.00	0.11	-54.50
Energy				
. Purchased Fuel				
- Coal	10 ⁶ BTU	1.50	16.31	24.47
- Coke	Short Ton	50.00	1.24	62.00
. Electric Power Purchased	kWh	0.03	11,725.00	351.75
Water				
. Process	10 ³ Gal	0.70	1.54	1.08
. Cooling	10 ³ Gal	0.07	140.00	9.80
Direct Operating Labor (Wages)	Man-HR	9.54	6.13	58.48
Direct Supervisory Wages	15% Op. Lbr.			8.77
Maintenance Labor (Wages)	Man-HR	9.94	8.40	83.24
Maintenance Supervision (Wages)	15% Mnt. Lbr.			12.49
Maintenance Materials & Supplies	2.5% of CI			67.19
Labor Overhead	32% of Wages			52.15
Misc. Variable Costs/Credits				15.98
. Other Operating Supplies				<u>16.55</u>
TOTAL VARIABLE COSTS				810.78
FIXED COSTS				
Plant Overhead	60% of Wages			97.79
Local Taxes and Insurance	2% of CI			53.76
Depreciation	7.1% of CI			<u>190.83</u>
TOTAL PRODUCTION COSTS				<u>1,153.16</u>
Return on Investment (Pretax)	20% of CI			537.60
Pollution Control				<u>54.26</u>
TOTAL				1,745.02

TABLE 3-8

ESTIMATED PRODUCTION COSTS FOR NEW ALUMINUM PLANT, 1980
(ALCOA CHLORIDE PROCESS)

Product: Aluminum Process: Alcoa Chloride Location: Gulf Coast
 Annual Capacity: 160,000 Short Tons Capital Investment: \$406,799,000 Annual Production: _____

	Units Used In Costing Or Annual Cost Basis	\$/Unit	Units Consumed Per Short Ton Of Aluminum	\$Per Short Ton Of Aluminum
VARIABLE COST				
Raw Materials				
. Bayer Alumina	Short Ton	394.00 (A)	1.93	760.41
. Oxygen	Short Ton	20.00	0.02	0.40
. NaCl	Short Ton	30.00	0.0001	0.03
. LiCl	Short Ton	2,000.00	0.001	2.00
. Chlorine	Short Ton	150.00	0.19	29.50
Byproduct Credits				
. 35% HCl Solution	Short Ton HCl	37.80	-0.19	-7.18
Energy				
. Purchased Fuel (No. 6 Fuel Oil) 10 ⁶ BTU		5.00	24.85	124.85
. Electric Power Purchased kWh		0.030	10,500.00	315.00
- Miscellaneous	-	-	-	-
Water				
. Process	10 ³ Gal	0.70	0.2	0.14
. Cooling	10 ³ Gal	0.07	100.00	7.00
Direct Operating Labor (Wages)	Man-HR	9.54	3.5	33.39
Direct Supervisory Wages	15% Op. Lbr.			5.01
Maintenance Labor (Wages)	Man-HR	9.54	4.5	42.93
Maintenance Supervision (Wages)	15% Mnt. Lbr.			6.44
Maintenance Materials	2.5% of CI			63.56
Labor Overhead	32% of Wages			28.09
Misc. Variable Costs/Credits	-	-	-	-
TOTAL VARIABLE COSTS				<u>1,410.57</u>
FIXED COSTS				
Plant Overhead	60% of Wags			52.66
Local Taxes and Insurance	2% of CI			50.85
Depreciation	7.1% of CI			<u>180.52</u>
TOTAL PRODUCTION COSTS				<u>1,694.60</u>
Return on Investment (Pretax)	20% o CI			508.50
Pollution Control				<u>23.10</u>
TOTAL				2,226.20

(A) See Table 5.1

3.2.3 Geographic Cost Indices

It is well known that there are geographic differences in the cost of constructing an identical facility or installation at various locations within the United States or throughout the world. For our study, we have chosen to use the construction cost indices developed by the U.S. military construction agencies on the basis of various commercial surveys and from actual Department of Defense bid experience. Washington, D.C., is used as a base of 1.00.

Table 3-9 lists the geographic construction cost indices for various locations where OTEC installations might be considered. It is seen that for most of the U.S. Gulf Coast area, the index is about 1.00.

For purposes of analysis, we have assumed that for a Bayer plant, a Toth plant, or a reduction plant to be built at a foreign location that only 55% of the capital costs (if the plant was costed to be located in the U.S.) would be subject to the geographical construction cost index, representing work done at the site, and that 45% of the capital cost would represent equipment fabricated somewhere else in the world and shipped to the site for installation.

As will be seen in the economic analyses, the capital cost differential for building production facilities on many islands where the OTEC resource is favorable tends to equalize the apparent thermal resource benefits of such sites.

3.2.4 Geographic Wage Rates

As may be seen from Tables 3-2 through 3-8, labor costs are an important factor in estimated production costs. When foreign locations are considered, there is a considerable variation in wages paid for skilled labor and their productivity. The following geographic labor cost indices were used in this study.

<u>Location</u>	<u>Index</u>
U. S. Gulf Coast	1.0
Puerto Rico	0.62
U. S. Virgin Islands	0.6
Guam	0.88
Mindanao, P.I.	0.30

They were based on the highest category of skilled labor and were derived from data provided by sources such as the Virgin Islands Industrial Development Commission, the Puerto Rico Economic Development Administration, etc.

In our economic analyses, we assumed that the crews on the OTEC plantships would work 84 hours per week, 12 hours/day for 7 days, similar to the crews on maritime vessels or offshore drilling platforms. The U.S. wage rate was assumed to be \$16.30/hr which, when combined with supervision and fringe benefits, comes to \$24.75/hr.

Because of uncertainty over potential crew compensation rates which might be connected with loan guarantees or other regulations relating to the nation of registration of the plantship, we did not apply the above geographic

TABLE 3-9

GEOGRAPHIC CONSTRUCTION COST FACTORS *
CONTINENTAL UNITED STATES, OVERSEAS AREAS AND FOREIGN COUNTRIES

PLACE	FACTOR	PLACE	FACTOR
<u>Southwest U. S.</u>		<u>Foreign Countries (Cont'd)</u>	
Alabama - Gulf Coast Area	0.97	Brazil	1.50
Florida - South	1.15	British Guiana	1.20
Florida - Key West	1.00	British Honduras	1.00
Georgia - South	1.00	British West Indies - Antigua	1.40
Louisiana - New Orleans	1.00	British West Indies - Barbados and Trinidad	1.20
Mississippi - South	0.99	Burma	1.40
South Carolina - South	1.00	Carolina Islands - Tizuk	2.00
Texas - South	0.98	Ceylon	1.10
Texas - Matagorda Island	1.05	Christmas Islands	2.20
		Colombia	1.30
		Costa Rica	1.00
		Cuba - Guantanamo Bay	1.60
		Ecuador	1.50
		El Salvador	1.00
		Ethiopia - Eritrea	.90
		Formosa (Taiwan)	.70
		French Guiana	1.20
		Guatemala	1.00
		India - Bombay	.90
		Japan - Southern Area	1.00
		Korea	.90
		Liberia	.80
		Mexico - Mexico City	1.00
		Nicaragua	1.00
		Pakistan - West Karachi	1.20
		Peru	1.50
		Philippine Islands	1.00
		Saudi Arabia - Dhahran	1.50
		Somaliland	1.20
		Surinam - Netherland Guiana	1.20
		Thailand	1.80
		Venezuela	1.30
		Vietnam - Saigon Area	2.20
		Vietnam - Other Areas	2.50
		Volcanic Islands - Iwo Jima	2.20
<u>U.S. Islands</u>			
Canal Zone - Land	1.50		
Caroline Islands - Tizuk, Truk	2.00		
Hawaii - Oahu	1.20		
Hawaii - Kauai	1.80		
Hawaii - Other Islands	1.60		
Johnston Islands	2.40		
Line Islands - Palmyra	2.00		
Mariana Islands - Guam, Siapan, Tinian	2.00		
Midway Island	2.4		
Puerto Rico - San Juan Area	1.4		
Puerto Rico - Roosevelt Roads Area	1.5		
Samoa	2.4		
Virgin Islands	1.3		
Wake Island	2.2		
<u>Foreign Countries</u>			
Argentina	1.90		
Australia - North Coastal Areas	2.30		
Azores	1.10		

*(Source DOD 4270.1-CG Fy 82)

labor cost indices to the OTEC plantship crew costs in our economic analyses, although the labor hours are segregated so that this can be done.

3.2.5 Estimated Costs of OTEC Power System Components

There have been a number of estimates for the costs of the components of basic OTEC plantships (before adding the onboard processing plant). For this report, we used the MITREK OTEC technology forecast tree⁽³⁹⁾ for the basic data on the 8th 400-MWe commercial plant, off New Orleans, LA. With ΔT assumed 22°C (40°F).

Table 3-10 gives the cost breakdown derived from this source for ΔT 's of 20°C and 24°C using the scaling suggested by Douglass and Bakstad from a cost variation curve which is usually approximated by $(\Delta T)^{-1.8}$.*

The power system component costs were based on aluminum plate and fin heat exchangers. The ship hull cost was assumed to be divided evenly between the hull and the mooring system. The cold water pipe was assumed to be made of fiber reinforced plastic (FRP) and the estimated cost was assumed as an average of the NOAA FRP, SAI FRP, and TRW FRP costs.

From systems studies, it was concluded that if 100 MWe plantships were to be built rather than the 400 MWe plantships on which the cost estimates were made, that the costs per kilowatt should be increased by about 16% to account for the off optimum design conditions, or \$349/kW for the $\Delta T = 22^\circ\text{C}$ base case. We assumed that there was no penalty for increasing the output to 500 or 600 MWe from a single plantship.

* G. Dugger (private communication) suggests that the exponent should be in the -2.6 to -2.8 range.

TABLE 3-10

COSTS ASSUMED FOR THE COMPONENTS OF THE BASIC OTEC PLANTSHIP (400-500 MWe)

	$\Delta T = 22^\circ\text{C}$	$\Delta T = 20^\circ\text{C}$	$\Delta T = 24^\circ\text{C}$
Extrapolation Factors*	1	11/9	8/9
	\$/kw	\$/kw	\$/kw
Power System (Heat exchanger, turbo alternator, sea water pumps, other power units)	991.0	1211	881
Hull (platform)	220	269	196
Mooring	220	269	196
Miscellaneous	61	75	54
Cold Water Pipe	448	547	398
Transmission (100 mile cable)	232	284	206
	<u>2172</u>	<u>2655</u>	<u>1931</u>
Additional Cost for 100 MWe Units	349	427	310

*NB: Extrapolation factors from Douglass and Bakstad. (Ref. 4)

20°C = 36°F, 22°C = 39.6°F, 24°C = 43.2°F

3.3 Case History Analysis

3.3.1 Shore-Based Bayer-Hall Process Plant on U. S. Gulf Coast

To serve as a baseline case for our economic comparison, we chose the combination of a conventional Bayer process plant and a Hall process reduction plant to be constructed, on a "green field" site, starting in 1981, at a location along the U. S. Gulf Coast and that such a plant theoretically would be able to receive power through a cable from an offshore OTEC power plant, the system configuration shown in Figure 1-7. As outlined in Appendix A, Case A1.1, the Bayer plant capacity is 700,000 MT/yr of Al_2O_3 , and the corresponding capacity of the reduction plant is 362,700 MT of aluminum metal requiring approximately 637 MWe.

We have assumed that electricity would be available at the site at the rates 5, 10, 15, 20, 30, and 40 mills per kWh in 1980. The estimated cost of electricity in this area in 1980 is 30 mills/kWh. It was assumed that electricity prices will escalate at the rate of 20% per year through 1985, then at 10% per year through 1990, then drop to the embedded 7% inflation rate thereafter. Table 3-11 displays the expected electricity cost escalation factors, by quarter, for the next 33 years. This model is based on the assumption that the present prices for electricity in the United States are artificially low, below replacement costs, because of a number of institutional factors and that it will take a period of time for the rate setting mechanisms to allow for the true costs to be represented in the rate structure. It is assumed that the prices for raw materials, labor, and other materials used in the project will escalate at the embedded inflation rate of 7%, as well as the sales price of the product. The estimated capital cost of this project is \$1,278 million and the estimated cost of raw materials, labor maintenance, and other operating costs exclusive of electricity are \$845/MT (\$766.51/t) of aluminum metal. Appendix A Case A1.1 gives a breakdown of the capital costs of this project, and the operating costs in 1980 dollars. These costs are escalated by the GNP deflator during the 33 year life of the project, three years of construction and 30 years of operation. The projected Rate of Return on Investment (ROI) is given in Figure 3-5 as a function of the 1980 cost of electricity for the two electricity cost escalation scenarios.

Figure 3-6 shows the rate of return for the Gulf Coast Bayer-Hall complex as a function of the cost of electricity for three levels of financing (debt): 0% (entirely financed internally), 30% financed (70% equity), and 80% (20% equity). The 0% financing was chosen to represent the return on assets, and the other two cases were chosen to bracket the weighted range of project debt-to-equity ratios which could be realized if the OTEC portion of the project, to be discussed in other case histories, could be covered with the 87-1/2% MARAD loan guarantee. This data is also given in Table 3-12.

It is seen that at a 5 mill/kWh cost of electricity (which will not be available for any new plants) the rate of return is approximately 9% for all cases. As the cost of electricity increases, so that the project becomes

TABLE 3-11
ASSUMED ELECTRICITY INFLATION FACTORS
(BY QUARTERS)

Year	Annual Rate	Quarter			
		1st	2nd	3rd	4th
1981	20%	1.047	1.095	1.147	1.200
1982	20%	1.256	1.315	1.376	1.440
1983	20%	1.507	1.577	1.651	1.728
1984	20%	1.809	1.893	1.981	2.074
1985	10%	2.170	2.272	2.377	2.488
1986	10%	2.548	2.610	2.673	2.737
1987	10%	2.803	2.871	2.940	3.011
1988	10%	3.083	3.158	3.234	3.312
1989	10%	3.392	3.474	3.557	3.643
1990	7%	3.731	3.821	3.913	4.007
1991	7%	4.076	4.145	4.216	4.288
1992	7%	4.361	4.436	4.511	4.588
1993	7%	4.666	4.746	4.827	4.909
1994	7%	4.993	5.078	5.165	5.253
1995	7%	5.343	5.434	5.526	5.621
1996	7%	5.717	5.814	5.913	6.014
1997	7%	6.117	6.221	6.327	6.435
1998	7%	6.545	6.657	6.770	6.886
1999	7%	7.003	7.122	7.244	7.368
2000	7%	7.493	7.621	7.751	7.883
2001	7%	8.018	8.155	8.294	8.435
2002	7%	8.579	8.725	8.874	9.026
2003	7%	9.180	9.336	9.495	9.657
2004	7%	9.822	9.990	10.160	10.333
2005	7%	10.510	10.689	10.871	11.057
2006	7%	11.245	11.437	11.632	11.831
2007	7%	12.033	12.238	12.447	12.659
2008	7%	12.875	13.094	13.318	13.545
2009	7%	13.776	14.011	14.250	14.493
2010	7%	14.740	14.992	15.248	15.508
2011	7%	15.772	16.041	16.315	16.593
2012	7%	16.876	17.164	17.457	17.755
2013	7%	18.058	18.366	18.679	18.998

Fig. 3-5. Rate of return on investment for baseline case of new Bayer-Hall complex on U.S. Gulf Coast as a function of 1980 electricity cost, for constant and variable escalation rates.

Fig. 3-6. Rate of return on investment for Bayer process Hall process complex on U.S. Gulf Coast producing 362,000 MT/yr of aluminum ingot, as a function of the purchase cost of electricity in 1980 for various financing options.

more marginal, the cash flow for interest and principal repayments has a strong effect on the profit margin. Under these conditions, which would occur for an initial cost of electricity of about 15 mills/kWh, the 0% financing case is the most favorable--it just breaks even.

As shown in Figure 3-2, the aluminum industries' return on invested capital is about 12%, and it is expected that any major investment made by any of the companies would be expected to provide a greater rate of return than this in order to improve the overall profitability of the industry. Increasing the rate of return would make raising of the capital required for the indicated expansion of capacity more attractive. With an investment "threshold" of the order of 12% or higher, it is highly unlikely that any company would elect now to build a greenfield Bayer-Hall aluminum production complex at a site along the U. S. Gulf Coast where the present cost of electrical power is less than the level required for breakeven operation.

Inherent in the calculation of the rates of return shown in Figure 3-6 is the assumed rate of escalation of electricity costs given in Table 3-11. If we were to have assumed instead that the electricity cost would only escalate as the GNP deflator (assumed 7%), along with wages, other production costs and the sales price, then the rates of return would be higher as shown in Table 3-12 in the second column under the internally financed assumption, but still marginal.

OTEC Powered Plant

For this case, we have assumed the same Bayer-Hall aluminum production complex on the U. S. gulf Coast, powered by a 637 MWe OTEC plantship located 100 miles offshore in the Gulf of Mexico where ΔT is 20°C, with the electrical energy brought to the plant by an undersea high voltage d.c. cable. The capital cost of the OTEC power plantship and cable were \$2,655/kW. Appendix A, Case A1.2 gives the details.

It was assumed that the operating and maintenance costs of the OTEC power system and cable would be 2-1/2% of the capital investment, exclusive of the OTEC crew cost; that the OTEC plant would have an annual load factor of 0.90; and that the remainder of the electricity required would be purchased from the local utility grid at the price of \$0.030/kWhr in 1980, with the cost escalated as in Table 3-11.

It was assumed that the shore facilities would be financed either with 0%, 30%, or 80% debt, that the OTEC power system could be covered by an 87.5% MARAD loan guarantee, and that the OTEC power system would be eligible for the 15% solar energy investment tax credit. The ROI's projected for this case are given in Table 3-13. On the basis that the investment tax credits would be limited to the tax liability of this project, the return was less than 5%. By assuming the higher income tax liability, rates of return in the range of 7 to 8% were projected for this project.

The use of molten carbonate fuel cells, fueled with OTEC derived ammonia to power the Bayer-Hall complex was examined. The financial details are given in Appendix A, Case A1.3, while technical details of integrating the fuel cells and the production facilities are presented in Appendix B. Ammonia prices greater than \$125/ton yielded negative rates of return under all conditions.

TABLE 3-12

RETURN ON INVESTMENT OF BAYER-HALL PRODUCTION FACILITIES ON
U.S. GULF COAST, CONVENTIONAL POWER SOURCE, AS A FUNCTION OF
PURCHASED ELECTRICITY COST (1980 BASE),
FOR VARIOUS LEVELS OF FINANCING
(CASE A1.1)

Initial Electricity Cost	Internal Rate of Return Percent Financed			
	0%	0%	30%	80%
Mills/kWhr	(1)	(2)	(1)	(1)
0	16.3	16.3	17.6	24.0
5	14.1	15.2	15.0	18.9
10	11.5	14.0	12.0	13.7
15	8.4	12.7	8.5	8.2
20	4.3	11.4	3.9	2.0
30	0	8.3	0	0
40	0	4.3	0	0

(1) Electricity cost escalated at rate given in Table 3-11.

(2) Electricity cost escalated at constant rate of 7%, the same
as aluminum sales price and the general rate of inflation.

TABLE 3-13

RETURN ON INVESTMENT OF BAYER-HALL
PRODUCTION FACILITIES ON U. S. GULF COAST,
POWERED BY OTEC PLANTSHIP
WITH $\Delta T = 20^{\circ}\text{C}$, 100 MILE CABLE

Production Facilities	Portion Financed Portion Financed	OTEC Facilities	Return on Investment	
			ITC Limited to Project	ITC \$3 B Tax Liability
%		%	%	%
0		0	4.9	7.2
30		87.5	3.8	7.8
80		80	2.5	7.7

3.3.2 Onshore Bayer-Hall Complexes at Overseas Locations Powered by OTEC

Capital and production costs were estimated for Bayer-Hall complexes in Guam, Virgin Islands, Puerto Rico, and Mindanao (the estimates can be found in Tables A-2 through A-6 in Appendix A) and cash flow analyses were performed with different financing schemes. The rates of return are presented in Part A of Table 3-14.

The capital and production costs are higher on the Island of Guam under the assumed conditions and the rates of return are of the order of 5%, irrespective of investment tax credit or financing.

The labor costs are low in the Island of Mindanao, as are the estimated capital costs due to a ΔT of 24°C and a construction cost geographic index of 1.0. As previously cited, the tax structure is different from that in the U.S.A. These factors result in a projected rates of return of 11 to 12%.

In the case of the Virgin Islands, the tax structure is basically 90% of the U.S. tax for the first 15 years of the project then increases to U.S. tax code rates. Capital costs are high with a construction cost geographic index of 1.3 and the cost of energy which must be purchased is high, resulting in higher production costs. The result is projected rates of return of 7 to 8%.

The tax structure in Puerto Rico is entirely different; the tax being 4.5% for the first 5 years, 11.25% the next 5 years, 15.75% the next 5 years, 20.25% the next five, 22.25% the next 5 years, and then a maximum of 45% from then on. The higher capital and production costs on Puerto Rico result in rates of return of 4 to 5%.

3.3.3 Bayer-Drained Cathode Hall Cell Complexes

For the Drained Cathode Hall cell cases (Tables B1-B3 in Appendix A), the plants were assumed to be located on shore. Since the cost of land has only a small effect on total cost, a low current density of 7 kA/m^2 was assumed. The returns are summarized in Part B of Table 3-14. Rates of return range between 6% for Guam and 11.1% for Mindanao.

As observed in Section 2.4, the Drained-Cathode cell is not susceptible to oscillations, hence it can be mounted on a plantship. Two cases (Table C1 and C2 in Appendix A) were investigated as summarized in Part C of Table 3-14. Since the cost of hull increases steeply with the deck area, a higher current density of 14 kA/m^2 was assumed. The Bayer plants were located on shore. The projected rates of return ranged between 3.5 and 7.7%. For the cases with the plantship on the U.S. Gulf Coast, the projected returns for the plantship are lower than for equivalent capacity powered by an OTEC plantship through a cable.

TABLE 3-14

RATES OF RETURN FROM BAYER-HALL PLANTS

SALES PRICE = \$1590/MT (1980)

Location	% Financed	Rate of Return	
		(1)	(2)
<u>A. Conventional Reduction Plants with OTEC Power By Cable</u>			
Guam	0		5.4
	51.9		3.5
Mindanao	0	11.1	
	80	12.4	
Puerto Rico	0	5.6	
	55.5	3.6	
Virgin Islands	0		8.2
	56.1		6.9
<u>B. Drained-Cathode Reduction Plants on Shore with OTEC Power by Cable</u>			
U. S. Gulf Coast	0		7.7
Guam	0		6.0
Mindanao	0	11.1	
<u>C. Drained-Cathode Reduction Plants on Plantships</u>			
U. S. Gulf Coast	0	3.5	5.6
Guam	0		7.7
	70.7		5.8

(1) ITC is limited to the project tax liability

(2) ITC can be taken in full in first year of operation because owners have sufficient profits from other activities to fully utilize the ITC in that year.

3.3.4 Aluminum Chloride Reduction Plants Powered by OTEC Through a Cable

We have assumed a plant complex which uses the Toth process to chlorinate kaolin clay to produce AlCl_3 which is then reduced in bipolar cells to produce aluminum metal, with the chlorine being recycled to the chlorination process as described in Section 2.5 and Table 3-7. A throughput of 362,700 MT/yr was assumed, which would require 510 MWe of OTEC power. Because of the flexibility of starting and stopping the process, it was assumed that unlike the Hall process plants previously considered, 100% standby power would not be required. Therefore, purchased electricity was not included in the estimated production costs.

Results from Tables D1 through D5 in Appendix A are summarized in Table 3-15, Part A. The projected rates of return vary between 10.8 and 18.4%, depending upon location and ability to use the investment tax credit. Most of the projected rates of return are higher than our assumed 12% "threshold" for investment.

3.3.5 OTEC/Aluminum Chloride Process Plantships

The floating aluminum chloride plantship was discussed in Section 2.5. The capital costs for this model are derived from four systems: 1) the chlorination plant; 2) the OTEC power system; 3) the floating reduction plant and storage systems; and, 4) the transportation system. As discussed in Section 2.6, the reduction plant fits comfortably on the deck of the 100-MWe OTEC plantship hull. If the barges can transfer a six to seven day supply of reactants to and from each plantship during a two-day roundtrip (and the plantship can store this amount), then two barges can support the five 100-MWe plantships. Also required at the shore support base are loading and unloading equipment, chlorine storage, and a cast house for remelt of the aluminum particles and casting into desired forms for further processing.

Results for 5 cases from Tables E1, E2, E3, E4, and E5 of Appendix A are summarized in Part B of table 3-15. In cases E1, E3, and E5, one shore base supports five nominal 100-MWe chloride reduction plantships. In case E2, one larger shore support base supports two nominal 400-MWe plantships. All cases show positive rates of return which range from 8.9 to 17.9%. The results for the two plantship versus five plantship configurations show the economics of scale.

The chloride process plantships, when compared to the drained cathode Hall process plantships under similar financial condition at Guam and the U.S. Gulf Coast yield higher ROI's by 7.3% and 5.7% respectively.

It may also be noted that the projected ROI's for shore based chloride process plants was about 2% to 4.5% higher than the plantship cases. Much of this penalty for the plantship cases is due to the cost of the facilities for moving AlCl_3 and Cl_2 back and forth from the plantship to shore. Performing the chlorination aboard the plantship, as discussed in section 2.5.1, should alleviate this penalty.

We conclude that the chloride processes, either powered by OTEC through a cable or as OTEC/aluminum plantships, yield the most attractive projected rates of return for any of the options examined in this study.

TABLE 3-15

RATES OF RETURN FOR ALUMINUM
CHLORIDE REDUCTION PLANTS

Location	% Financed	Rate of Return	
		(1)	(2)
<u>A. Reduction Plants on Shore</u>			
U.S. Gulf Coast	64.8	12.2	18.4
	0	10.8	13.0
Guam	52.7	14.8	16.9
	0	13.7	15.0
Mindanao	0	17.6	
Puerto Rico	0	17.1	
Virgin Islands	0		18.3
<u>B. Reduction Plants on Plantships</u>			
U. S. Gulf (461.2 MWe	72.8	9.3	17.0
5 Plantships, 362,700 MT/yr)	0	8.9	11.3
U.S. Gulf (744.6 MWe	74.2	11.4	17.9
2 Plantships, 580,320 MT/yr	0	10.2	12.2
Guam (461.2 MWe, 362,700 Mt/yr)	0		13.1
Mindanao (461.2 Mwe, 362,700 MT/yr)	0	13.7	
Virgin Islands (461.2 MWe, 362,700 MT/yr)	0		13.7
Puerto Rico (461.2 MWe, 362,700 MT/yr)	0	13.1	

(1) ITC is limited to the project tax liability

(2) ITC can be taken in full in first year of operation because owners have sufficient profits from other activities to fully utilize the ITC in that year.

4.0 SUMMARY AND CONCLUSION

4.1 Process Comparisons

It was concluded early in the study that the conventional Hall reduction process was not suitable for operation on an OTEC plantship because of electrical shorting. Methods for stabilizing the platform in pitch and roll in response to wave action resulted in heaving motion, which also could lead to shorting.

The drained-cathode Hall cell would be an improvement, and it may be technically feasible, but its high capital costs and space requirements for such an installation onboard an OTEC plantship make it unattractive, too, for the cases evaluated.

Because of the large quantities of materials which would have to be hauled from the shore base to the OTEC/aluminum plantship, and then back to the shore base; i.e., anode stubs, scrubber liquor, cathode assemblies for repair, in addition to the basic raw materials and finished products; it is not clear that the drained-cathode Hall process, or even the chloride reduction process where chlorination was conducted on the shore, could ever be operated in a "grazing" plantship mode.

The chloride reduction process appears to be better suited for the OTEC application for the following reasons:

- a) It should be relatively motion tolerant in a plantship environment.
- b) It is more efficient in the use of electricity and therefore should have lower capital costs for the OTEC power system per unit of annual capacity.
- c) It can be arranged in bipolar cell stack assemblies which require an order of magnitude less deck area on a plantship. Our studies show that the physical characteristics of the closed cycle OTEC system require a given hull size per unit of electrical output and that a chloride reduction plant could easily fit on the deck of an OTEC platform with the appropriate electrical output.
- d) Because a metal "pad," or pool of aluminum is not required for the bipolar aluminum chloride reduction cells to operate, they should be much easier to start up and shut down than the conventional Hall cells. Therefore, complete backup electrical power for 100% of the time will not be required. This is important for both the plantship applications and for land-based applications where the OTEC power is either provided by cable or from a shore-based OTEC plant.

However, because the processes for producing aluminum trichloride from either bauxite or kaolin clays and the chloride reduction process itself have never been operated in extensive commercial practice, there is some degree of uncertainty over some of the technical details and economics for using the chloride process to produce aluminum in the OTEC context.

One serious operational problem with respect to the chloride process we have addressed is the issue of transferring in a running sea the AlCl_3 from the support ship to the plantship, and the metal product and recycle chlorine back to the support ship. The technical solution suggested is to convert the aluminum product to a coarse metal powder so that the AlCl_3 and aluminum metal can be moved by pneumatic transport through a single point mooring attachment. However, because of the hygroscopic nature of the AlCl_3 , its transport in a marine environment and transfer at sea may result in unacceptable product losses without extensive technical support systems for this operation. Therefore, from a logistical and operational standpoint, the most desirable process configuration would be to perform the chlorination aboard the plantship. The transportation problems then become one of moving calcined bauxite or clays and some form of carbon such as green coke from the shore base to the plantship, transferring the cargo by pneumatic conveying, then return to shore with a hold full of the aluminum particles. Unfortunately, a detailed study of a plantship involving an onboard chlorinator was beyond the scope of the present study, but preliminary calculations suggest that it may be feasible and would result in a lower capital cost for the overall project. With onboard chlorination, the OTEC/aluminum plantship could possibly be free to operate in the grazing mode where it can move seasonably to the areas with the highest ΔT 's.

Economic analyses of the various OTEC/aluminum options concluded that use of the Hall process either as conventionally configured, or with the drained-cathode design, in a new facility using an OTEC energy source would not be economical with the construction, labor and energy costs comparable to those in the United States. These analyses projected that use of the Toth chlorination process to chlorinate kaolin clays to produce AlCl_3 , followed by electrolytic reduction to aluminum metal in bipolar cells would yield rates of return in the region of 8.9 to 18.4% when using OTEC energy. The projected rates of return are sensitive to income tax rates and investment tax credits.

4.2 Alternate Energy Sources for the Aluminum Industry

As background to these results, let us note the following locations in the world where there are potential hydroelectric resources which can be utilized by the aluminum industry:

North America - There are many potential hydroelectric sites in Alaska. Alcan has proposed a dam and hydroelectric station to increase the output of their smelter at Kitimat, British Columbia. There are untapped hydroelectric sites in Eastern Canada at James Bay and on Labrador.

South America - The ITAPU project on the Parana River between Brazil and Paraguay, which is 65% complete, will have a capacity of 13,000 MWe. The Jassurita project on the Parana River between Paraguay and Argentina will have a capacity of 5,000 MWe. Venezuela, Guyana, Columbia, and Costa Rico also have potential hydroelectric sites. Many of these countries also have native sources of bauxite.

Africa - The Zaire River (formerly the Volta River) has identified sites for 60,000 to 70,000 MWe of hydroelectric power. Central Africa has many sites where extensive hydroelectric development would be feasible.

Asia and South East Asia - The Peoples Republic of China has several hydroelectric sites which are suitable for aluminum smelters. Malaysia, Indonesia, the Philippine Islands, New Guinea, and New Zealand have potential hydroelectric power resources. An aluminum plant is now being planned for New Zealand, while the Malaysian and Philippine Island governments have announced that they are considering aluminum smelting projects.

It is against this background that the aluminum industry must consider OTEC as an energy source. The OTEC option is similar to the hydroelectric option in that both are capital intensive at the start and have essentially free fuel. The advantages that OTEC would have for the U. S. aluminum industry would be avoidance of the political risk of using hydroelectric energy at some foreign sites and avoidance of sending more of U.S. money overseas (the balance of payments problem).

At some time in the reasonably near future, the good hydroelectric sites will have all been developed, as has happened in the United States, and the aluminum industry may turn to OTEC as a major source of its electrical energy. Presumably by the mid 1990's (per PL 96-310) a healthy OTEC industry will have been developed for the electrical utility market and OTEC power systems will have been demonstrated in commercial operation for extended periods of time. The aluminum industry should monitor this OTEC development, beginning with the 40-MWe pilot/demonstration plants that are called for by 1986, and conduct further economic evaluations to be ready for decisions before 1990 as to when it should begin using OTEC energy.

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APPENDIX A: SUPPORTING COST ESTIMATES

The capital and production costs and the relevant details are listed in this appendix. The tables are presented in the following order:

Table A. Bayer-Hall plants located on shore.

Table B. Bayer-drained cathode plants located on shore.

Table C. Bayer plant on shore, drained cathode cells on plantships.

Table D. Toth-chloride plant on shore, OTEC power by cable.

Table E. Toth plant on shore, chloride reduction plant on plantships.

Further, numeral suffixes were added indicating the geographic locations as follows:

<u>Suffix</u>	<u>Location</u>
1.1	U.S. Gulf, Bayer-Hall Plant on Shore
1.2	U.S. Gulf, Same, powered by OTEC
1.3	U.S. Gulf, Same, powered by OTEC derived NH_3
2	Guam
3	Mindanao, PI
4	Puerto Rico
5	U.S. Virgin Islands

The capital costs of Bayer plants were extracted from Ref. 38, and scaled up with the throughput, $\dot{m}$, using the 0.7 power law and scaled in time using the Chemical Engineering plant cost index. The capital costs of Toth plants were extracted from Ref. 36, and scaled in a similar manner. The costs of the reduction plants were obtained from Ref. 36, and components were added or deleted depending on the reduction process and scaled with time and throughput. The production costs were obtained from Ref. 36, and modified using current costs of materials, labor rates. Further specific details and comments have been added to each set of tables. The manpower requirements for the specific OTEC options are presented as Tables B, C, D, and E. Superscripts refer to the comments on the particular set of cases, i.e., A on Page A-5, B on page A-12, etc.

TABLE A1.1 ESTIMATED CAPITAL AND PRODUCTION COSTS
FOR A BAYER-HALL 362, 700 MT/yr ALUMINUM
PLANT ON U. S. GULF COAST (1980 U. S. \$)

CAPITAL COSTS	\$ x 10 ⁶	Total
Cost of Bayer Plant	340.85	
Cost of Hall Plant	937.28	
Total		1,278.13
Cost of Land	23.60	
Cost of Offices	5.70	
Capital Cost for Investment Tax Credit		1,248.83

PRODUCTION COSTS	Units	\$/Unit	# of Units	\$ Per Short Ton	Bayer	Hall	Total
			Per Short Ton	of Aluminum			
<u>Raw Materials and Other</u>							
Bauxite	Short Ton	33.80	4.56	154.13			
Limestone	Short Ton	7.35	0.253	1.86			
Soda Ash	Short Ton	105.00	0.143	15.02			
Starch	Short Ton	260.00	0.011	2.86			
Cryolite	Short Ton	493.90	0.035			17.29	
Aluminum Fluoride	Short Ton	514.90	0.02			10.29	
Water				1.68			
Maintenance Materials	1.5% of C.I.			12.79			
Maintenance Materials	2.5% of C.I.					58.62	
				<u>188.34</u>	<u>86.20</u>		<u>274.54</u>
Purchased Fuel	10 ⁶ BTU	4.00	22.12	88.48			
Purchased Fuel	10 ⁶ BTU	4.00	6.60			26.40	
Calcined Coke	Short Ton	120.00	0.52			62.40	
Pitch	Short Ton	103.00	0.15			15.45	
				<u>88.48</u>	<u>104.25</u>		<u>192.73</u>
Labor	MH	14.50	3.19	46.26			
Labor	MH	14.50	8.00			116.00	
Plant Overhead (45% of Wages)				20.82		52.20	
Local Taxes & Insurance	2% of C.I.			17.06		46.90	
				<u>84.14</u>	<u>215.10</u>		<u>299.24</u>
Total							766.51

Energy

Electric Power (Bayer)	kWhr	Variable	531.0
Electric Power (Hall)	kWhr	Variable	13,780.0

TABLE A1.2 ESTIMATED CAPITAL AND PRODUCTION COSTS FOR A
BAYER-HALL 362,700 MT/yr PLANT ON U. S. GULF
COAST POWERED BY OTEC THROUGH CABLE (1980 U.S. \$)

CAPITAL COSTS		\$ x 10 ⁶		Total	
OTEC Plant Costs					
536.7 MW x 2655 x 10 ³ \$/MW		1,690.04			
Total Capital Cost for Solar Energy				1,690.04	
Tax Credit					
Capital Cost of Bayer Plant		340.85			
Capital Cost of Hall Plant		937.28			
TOTAL CAPITAL COST				2,968.57	
Non-Investment Tax Credit Costs		29.3			
CAPITAL COST FOR INVESTMENT TAX CREDIT				2,939.26	

		# of Units Per Short Ton		\$ Per Short Ton of Aluminum Hall +		
PRODUCTION COSTS	Units	\$/Unit	of Aluminum	Bayer	OTEC	Total
Raw Materials and Other						
Bauxite	Short Ton	33.80	4.56	154.13		
Limestone	Short Ton	7.35	0.253	1.86		
Soda Ash	Short Ton	105.00	0.143	15.02		
Starch	Short Ton	260.00	0.011	2.86		
Cryolite	Short Ton	493.90	0.035		17.29	
Aluminum Fluoride	Short Ton	514.90	0.02		10.29	
Water				1.68		
Maintenance Materials (Bayer)	1.5% of C.I.			12.79		
Maintenance Materials (Hall)	2.5% of C.I.				58.62	
Maintenance Materials (OTEC)	2.5% of C.I.				105.74	
Purchased Fuel - Bayer	10 ⁶ BTU	4.00	22.12	88.48	191.94	380.28
Purchased Fuel - Hall	10 ⁶ BTU	4.00	6.60		26.40	
Calcined Coke	Short Ton	120.00	0.52		62.40	
Pitch	Short Ton	103.00	0.15		15.45	
				88.48	104.25	192.73
Labor, Bayer	MH	14.50	3.19	46.26		
Labor, Hall	MH	14.50	8.00		116.00	
Labor, OTEC	MH	24.75	2.79		69.08	
Plant Overhead (45% of Wages)				20.82	83.29	
Local Taxes & Insurance (including the fuel cells)	2% of C.I.			17.06	131.49	
				84.14	399.86	484.00
Subtotal						1057.01
Energy						
Electric Power (10% of Total Requirement)	kWhr	0.03	53.1	1.59		
Electric Power (10% of Total Requirement)	kWhr	0.03	1378.0		41.34	
				1.59	41.34	42.93

TABLE A1.3 ESTIMATED CAPITAL AND PRODUCTION COSTS FOR A
BAYER-HALL 362,700 MT/yr PLANT ON
U.S. GULF COAST POWERED BY MOLTEN
CARBONATE FUEL CELL ON SHORE USING
OTEC PRODUCED AMMONIA (1980 U. S. \$)

CAPITAL COSTS		\$ x 10 ⁶	Total
Cost of Bayer Plant		340.85	
Cost of Hall Plant		861.32	
Cost of Molten Carbonate Fuel Cell Plant		<u>254.68</u>	
Total			1,456.85
Cost of Land		23.60	
Cost of Offices		<u>5.70</u>	
Capital Cost for Investment Tax Credit			1,427.55

PRODUCTION COSTS	Units	\$/Unit	# of Units Per Short Ton of Aluminum	\$ Per Short Ton of Aluminum		
				Bayer	Hall	Total
<u>Raw Materials and Other</u>						
Bauxite	Short Ton	33.80	4.56	154.13		
Limestone	Short Ton	7.35	0.253	1.86		
Soda Ash	Short Ton	105.00	0.143	15.02		
Starch	Short Ton	260.00	0.011	2.86		
Cryolite	Short Ton	493.90	0.035		17.29	
Aluminum Fluoride	Short Ton	514.90	0.02		10.29	
Water				1.68		
Maintenance Materials	1.5% of C.I.			12.79		
Maintenance Materials	2.5% of C.I.				<u>53.87</u>	
				<u>188.34</u>	<u>81.45</u>	<u>269.79</u>
Purchased Fuel - Bayer	10 ⁶ BTU	4.00	2.31	9.24		
Purchased Fuel - Hall	10 ⁶ BTU	4.00	6.60		26.40	
Calcined Coke	Short Ton	120.00	0.52		62.40	
Pitch	Short Ton	103.00	0.15		<u>15.45</u>	
				9.24	104.25	113.49
Labor	MH	14.50	3.19	46.26		
Labor	MH	14.50	8.00		116.00	
Plant Overhead (45% of Wages)				20.82	52.20	
Operation & Maintenance of MCFC					26.17	
Local Taxes & Insurance	2% of C.I.			17.06	55.84	
(including the fuel cells)						
				<u>84.14</u>	<u>250.21</u>	<u>334.35</u>
Total						717.63
Ammonia	Short Ton	Variable	3.76*			

*See Figure B-2

Comments on Case Al.1--The operating costs were derived using the quantities presented in Tables 3.2 and 3.5, updating the respective material and labor costs. For example, it was assumed that the basic labor rate for the mid-1980 was \$9.54/hr and that there would be 15% supervision and 32% fringe benefits added to the basic rate to obtain \$14.50/hr; that natural gas was available along the Gulf Coast for \$4.00 per million BTU, etc. The cost of purchased electrical power in 1980 was treated as a variable. The electrical rates were escalated from 1980 in accordance with Table 3-11.

The sales price of aluminum ingot was assumed as \$.72/lbm or \$1440/t = \$1587/MT (mid 1980). The sales price, and all costs other than electricity, were assumed to escalate at an annual rate of 7%.

Comments on Case Al.2--The costs of the OTEC power system components were developed from the MITRE OTEC Cost Forecast Tree for $\Delta T = 22^{\circ}\text{C}$, scaled by the Douglass-Bakstad method down to 20°C appropriate to a Gulf Coast OTEC site. It was assumed that the OTEC plant would provide 90% of the electricity required by both the Bayer plant and the Hall plant, and that the other 10% would be purchased from the local utility at rates equivalent to \$0.030/kWhr in 1980, escalated in accordance with Table 3.11.

The OTEC power system operation and maintenance costs were assumed equal to 2-1/2% of the capital investment, and that local taxes and insurance for the OTEC power system would be equal to 2% of the capital investment. Both of these costs were assumed to escalate with the GNP deflator at 7% per annum.

Comments on Case Al.3--In this case we examine the use of OTEC derived ammonia in molten carbonate fuel cells to power both the Hall plant and provide steam for the Bayer plant. Appendix B provides technical details for this configuration.

The Bayer alumina plant costs were obtained from Reference 38 and scaled to an output of 700,000 MT/yr using an 0.7 power scaling law, and updated to mid 1980 by the Chemical Engineering Cost Index, Fig. 3-4.

The capital cost estimate of the Hall process plant from Case Al.1 was modified to eliminate the substation and rectifiers, since the fuel cells produce direct current, and these items would not be needed.

The cost of the molten carbonate fuel cell system was assumed as \$400/kw (Ref. 40).

It was assumed, as shown in Figure B-1, that all electricity for both plants would be produced by the molten carbonate fuel cell and that the steam required for the Bayer process would also be derived from the fuel cell system.

CASE A2

ESTIMATED COST FOR A BAYER-HALL PLANT ON GUAM POWERED BY OTEC THROUGH CABLE
 Cable length = 3 miles; Annual Capacity: 362,700 MT/yr
 (1980 U. S. \$)

CAPITAL COST ESTIMATE	\$ x 10 ⁶	Total
OTEC Plant Costs		
636.7 MW x 1730.8 x 10 ³ \$/MW	1,102.00	
Total Capital Cost for Solar Energy		1,102.00
Tax Credit		
Capital Cost of Bayer Plant *	340.85	
Capital Cost of Hall Plant	1,452.78	
TOTAL CAPITAL COST		2,895.63
Non Investment Tax Credit Costs	29.3	
CAPITAL COST FOR INVESTMENT TAX CREDIT		2,2866.33

* Because of the shortage of fuel on Guam, it was assumed that the Bayer plant was built at another location, such as Australia, where the geographic cost index was 1.0.

ESTIMATED PRODUCTION COST		# of Units Per Short Ton of Aluminum	\$ Per Short Ton of Aluminum		
Unit	\$/Unit		Bayer	OTEC	Total
<u>Raw Materials and Other</u>					
Bauxite	Short Ton	33.80	4.56	154.13	
Limestone	Short Ton	7.35	0.253	1.86	
Soda Ash	Short Ton	105.00	0.143	15.02	
Starch	Short Ton	260.00	0.011	2.86	
Cryolite	Short Ton	493.90	0.035		17.29
Aluminum Fluoride	Short Ton	514.90	0.02		10.29
Water				1.68	
Maintenance Materials 1.5% of C.I. (Bayer)				12.82	
Maintenance Materials 2.5% of C.I. (Hall)				58.73	
Maintenance Materials 2.5% of C.I. (OTEC)				105.93	
			188.37	192.24	380.61
Purchased Fuel	10 ⁶ BTU	4.00	22.12	98.48	
Purchased Fuel	10 ⁶ BTU	4.00	6.60	26.40	
Calcined Coke	Short Ton	120.00	0.52	62.40	
Pitch	Short Ton	103.00	0.15	15.45	
			88.48	104.25	192.73
Labor (Bayer)	MH	12.75	3.19	40.67	
Labor (Hall)	MH	12.75	8.00	102.00	
Labor (OTEC)	MH	24.75	2.79	69.08	
Plant Overhead (45% of Wages)				18.30	76.99
Local Taxes & Insurance 2% of C.I.				17.09	131.73
			76.06	379.80	455.86
Subtotal					1,029.20
<u>Energy</u>					
Electric Power (10% of Total Requirement)	kWhr	0.10	53.1	5.31	
Electric Power (10% of Total Requirement)	kWhr	0.10	1378.0	137.80	
			5.31	137.80	143.11

CASE A3

ESTIMATED COSTS FOR A BAYER-HALL PLANT ON MINDANAO, POWERED BY OTEC THROUGH CABLE
 $\Delta T = 24^{\circ}\text{C}$; 3 mile cable; Annual Capacity: 362,700 MT/yr
 (1980 U.S. \$)

CAPITAL COSTS	\$ x 10 ⁶	Total
Cost of Bayer Plant	340.85	
Cost of Hall Plant	937.28	
Cost of OTEC Power System	1,102.00	
Total Capital Cost		2,380.13

Investment tax credit not applicable to Philippine Islands tax structure.

PRODUCTION COST		Unit	\$/Unit	# of Units Per Short Ton of Aluminum	\$ Per Short Ton of Aluminum		
					Bayer	Hall + OTEC	Total
<u>Raw Materials and Other</u>							
Dauxite	Chert Ton	33.80	4.56	154.13			
Limestone	Short Ton	7.35	0.253	1.86			
Soda Ash	Short Ton	105.00	0.143	15.02			
Starch	Short Ton	260.00	0.011	2.86			
Cryolite	Short Ton	493.90	0.035		17.29		
Aluminum Fluoride	Short Ton	514.50	0.02		10.29		
Water				1.68			
Maintenance Materials 1.5% of C.I. (Bayer)				12.79			
Maintenance Materials 2.5% of C.I. (Hall)					58.62		
Maintenance Materials 2.5% of C.I. (OTEC)					68.93		
				188.34	155.13	343.47	
Purchased Fuel	106 BTU	4.00	22.12	88.48			
Purchased Fuel	106 BTU	4.00	6.60		26.40		
Calcined Coke	Short Ton	120.00	0.52		62.40		
Pitch	Short Ton	103.00	0.15		15.45		
				88.48	104.25	192.73	
Labor (Bayer)	MH	3.04	3.19	9.70			
Labor (Hall)	MH	3.04	8.00		24.32		
Labor (OTEC)	MH	22.50	3.07		69.08		
Plant Overhead (45% of Wages)				4.37	63.49		
Local Taxes & Insurance 2% of C.I.				17.05	102.40		
				31.12	237.83	268.95	
Subtotal						805.15	
<u>Energy</u>							
Electric Power (10% of Total Requirement)	kWhr	0.020	53.1	1.06			
Electric Power (10% of Total Requirement)	kWhr	0.020	1378.0		27.56		
				1.06	27.56	28.62	

CASE A4

ESTIMATED COSTS FOR A BAYER-HALL PLANT ON PUERTO RICO, POWERED BY OTEC THROUGH CABLE
 $\Delta T = 22^{\circ}\text{C}$; 3 mile cable; Annual Capacity: 362,700 MT/yr
 (1980 U.S. \$)

CAPITAL COSTS	\$ x 10 ⁶	Total
Cost of Bayer Plant	415.84	
Cost of Hall Plant	1,143.48	
Cost of OTEC Power System	1,239.7	
Total Capital Cost		2,799.02

Investment tax credit not applicable to Puerto Rico tax structure.

PRODUCTION COSTS	Unit	\$/Unit	# of Units Per Short Ton of Aluminum	\$ Per Short Ton of Aluminum		
				Bayer	Hall + OTEC	Total
<u>Raw Materials and Other</u>						
Bauxite	Short Ton	33.80	4.56	154.13		
Limestone	Short Ton	7.35	0.253	1.86		
Soda Ash	Short Ton	105.00	0.143	15.02		
Starch	Short Ton	260.00	0.011	2.86		
Cryolite	Short Ton	493.90	0.035		17.29	
Aluminum Fluoride	Short Ton	514.90	0.02		10.29	
Water				1.68		
Maintenance Materials 1.5% of C.I. (Bayer)				15.61		
Maintenance Materials 2.5% of C.I. (Hall)					71.52	
Maintenance Materials 2.5% of C.I. (OTEC)					77.54	
				<u>191.16</u>	<u>176.64</u>	<u>367.80</u>
Purchased Fuel	10 ⁶ BTU	4.00	22.12	88.48		
Purchased Fuel	10 ⁶ BTU	4.00	6.60		26.40	
Calcined Coke	Short Ton	120.00	0.52		62.40	
Pitch	Short Ton	103.00	0.15		15.45	
				<u>88.48</u>	<u>104.25</u>	<u>192.73</u>
Labor (Bayer)	MH	9.00	3.19	28.71		
Labor (Hall)	MH	9.00	8.00		72.00	
Labor (OTEC)	MH	24.75	2.79		69.08	
Plant Overhead (45% of Wages)				12.92	63.49	
Local Taxes & Insurance 2% of C.I.				20.81	119.25	
				<u>62.44</u>	<u>323.82</u>	<u>386.26</u>
Subtotal						<u>946.79</u>
<u>Energy</u>						
Electric Power (10% of Total Requirement)	kWhr	0.092	53.1	4.89		
Electric Power (10% of Total Requirement)	kWhr	0.092	1378.0		126.78	
				<u>4.89</u>	<u>126.78</u>	<u>131.67</u>

CASE A4 -COMMENTS

The capital costs for the Bayer plant and Hall reduction plant were adjusted by assuming that 55% of the capital cost would be expended in Puerto Rico with a geographic location construction cost index of 1.4.

The basic labor rate index of 0.62 with respect to the U.S. Gulf Coast yields an average hourly rate of \$5.91/hr. This is based upon data provided by PUERTO RICO, U.S.A. (The Puerto Rico Economic Development Administration.)

The cost of electric power to be purchased from the local utility at \$0.092/kWhr was derived from a 1976 cost of \$0.07/kWhr given by MITREK, escalated at the rate of 7% to 1980.

CASE A5

ESTIMATED COSTS FOR A BAYER-HALL PLANT ON U. S. VIRGIN ISLANDS, POWERED BY OTEC
THROUGH CABLE $\Delta T = 22^{\circ}\text{C}$; 3 mile cable; Annual Capacity: 362,700 MT/yr
(1980 U.S. \$)

CAPITAL COSTS		\$ x 10 ⁶		Total		
Cost of Bayer Plant		397.09				
Cost of Hall Plant		1,091.93				
Cost of OTEC Power System		1,239.70				
Total Capital Cost				2,728.72		

PRODUCTION COSTS		# of Units Per Short Ton of Aluminum		\$ Per Short Ton of Aluminum Hall + Bayer OTEC Total		
Unit		\$/Unit		Bayer	OTEC	Total
<u>Raw Materials and Other</u>						
Bauxite	Short Ton	33.80	4.56	154.13		
Limestone	Short Ton	7.35	0.253	1.86		
Soda Ash	Short Ton	105.00	0.143	15.02		
Starch	Short Ton	260.00	0.011	2.86		
Cryolite	Short Ton	493.90	0.035		17.29	
Aluminum Fluoride	Short Ton	514.50	0.02		10.29	
Water				1.68		
Maintenance Materials 1.5% of C.I. (Bayer)				14.90		
Maintenance Materials 2.5% of C.I. (Hall)					68.29	
Maintenance Materials 2.5% of C.I. (OTEC)					77.54	
				190.45	173.41	363.86
Purchased Fuel	10 ⁶ BTU	4.00	22.12	88.48		
Purchased Fuel	10 ⁶ BTU	4.00	6.60		26.40	
Calcined Coke	Short Ton	120.00	0.52		62.40	
Pitch	Short Ton	103.00	0.15		15.45	
				88.48	104.25	192.73
Labor (Bayer)	MH	7.25	3.19	23.13		
Labor (Hall)	MH	7.25	8.00		58.00	
Labor (OTEC)	MH	24.75	2.79		69.08	
Plant Overhead (45% of Wages)				10.41	57.19	
Local Taxes & Insurance 2% of C.I.				19.87	116.67	
				53.41	300.94	354.35
Subtotal						910.94
<u>Energy</u>						
Electric Power	kWhr	0.06	53.1	3.19		
(10% of Total Requirement)						
Electric Power	kWhr	0.06	1378.0		82.68	
(10% of Total Requirement)						
				3.19	82.68	85.87

CASE A5 - COMMENTS

The capital costs for the Bayer plant and Hall process reduction plant were adjusted by applying the geographic location index of 1.3 to 55% of the cost. The power systems costs was taken from Table for $\Delta T = 22^{\circ}\text{C}$, with a 3 mile underwater cable.

The Bayer plant and Hall reduction plant labor index was assumed 0.5 relative to U. S. Gulf Coast costs, resulting in an average labor rate (mid 1980) of \$4.77/hr, based on information supplied by the U. S. Virgin Islands Industrial Development Commission.

The cost of electrical energy to be purchased from the Virgin Islands Water and Power Authority was provided by the U.S. Virgin Islands Energy Office.

The OTEC manpower requirements are the same as those presented in Table D of Case D2.

CASE B1

ESTIMATED COSTS FOR A BAYER-HALL PLANT ON U. S. GULF COAST, POWERED BY OTEC
 THROUGH CABLE $\Delta T = 20^{\circ}\text{C}$; 100 mile cable; Annual Capacity: 356,837 MT/yr
 (1980 U.S. \$)

CAPITAL COSTS		\$ x 10 ⁶		Total			
Cost of Bayer Plant		340.85					
Cost of Hall Plant(a)		1,089.19					
Cost of OTEC Power System		1,351.13					
TOTAL CAPITAL COST				2,781.17			
Cost of Land		23.60					
Cost of Offices		5.70					
CAPITAL COST FOR INVESTMENT TAX CREDIT				2,751.87			
Capital Cost for Solar Energy		1,351.13					
Investment Tax Credit							
<hr/>							
PRODUCTION COSTS		Unit	\$/Unit	# of Units Per Short Ton of Aluminum	\$ Per Short Ton of Aluminum		
					Bayer	OTEC	Total
<hr/>							
<u>Raw Materials and Other</u>							
Bauxite	Short Ton	33.80	4.56	154.13			
Limestone	Short Ton	7.35	0.253	1.86			
Soda Ash	Short Ton	105.00	0.143	15.02			
Starch	Short Ton	260.00	0.011	2.86			
Cryolite	Short Ton	493.90	0.035			17.29	
Aluminum Fluoride	Short Ton	514.50	0.02			10.29	
Water					1.68		
Maintenance Materials 1.5% of C.I.					13.00		
Maintenance Materials 2.5% of C.I.						107.33	
Maintenance (OTEC) 2.5% of C.I.						55.02	
Cathode Materials	Short Ton	36.00	1.00			36.00	
					<hr/>	<hr/>	
					188.55	225.93	414.48
<hr/>							
Purchased Fuel	10 ⁶ BTU	4.00	22.12	88.48			
Purchased Fuel	10 ⁶ BTU	4.00	6.60			26.40	
Calcined Coke	Short Ton	120.00	0.42			50.40	
Pitch	Short Ton	103.00	0.15			15.45	
					<hr/>	<hr/>	
					88.48	92.25	180.73
<hr/>							
Labor	MH	12.75	3.19	40.67			
Labor	MH	12.75	8.00			102.00	
Labor (OTEC)	MH	24.75	2.79			69.08	
Plant Overhead (45% of Wages)					18.30	76.99	
Local Taxes & Insurance 2% of C.I.					17.33	129.88	
					<hr/>	<hr/>	
					76.30	377.95	545.25
<hr/>							
Subtotal						1,049.46	
<hr/>							
<u>Energy</u>							
Electric Power (10% Bayer)	kWhr	0.03	53.10	1.59			
Electric Power (10% Hall)	Kwhr	0.06	1378.0			33.54	
					<hr/>	<hr/>	
					1.59	33.54	35.13

CASE B2

ESTIMATED COSTS FOR A BAYER-DRAINED CATHODE HALL PLANT ($j = 7 \text{ kA/m}^2$) ON GUAM
 POWERED BY OTEC THROUGH CABLE $\Delta T = 24^\circ\text{C}$; 3 mile cable
 Annual Capacity: 356,837 MT/yr (1980 U.S. \$)

CAPITAL COSTS	\$ x 10 ⁶	Total
Cost of Bayer Plant (at other location)	340.85	
Cost of Drained Cathode Hall Plant ^(b)	1,688.24	
Cost of OTEC Plant, 500 MW @ \$1730.8/kw	865.4	
TOTAL CAPITAL COST		2,894.49
Cost of Land	23.60	
Cost of Offices	5.70	
CAPITAL COST FOR INVESTMENT TAX CREDIT		2,865.19
Capital Cost for Solar Energy	865.4	
Investment Tax Credit		

PRODUCTION COSTS	Unit	\$/Unit	# of Units Per Short Ton of Aluminum	\$ Per Short Ton of Aluminum		
				Hall +		
				Bayer	OTEC	Total
<u>Raw Materials and Other</u>						
Bauxite	Short Ton	33.80	4.56	154.13		
Limestone	Short Ton	7.35	0.253	1.86		
Soda Ash	Short Ton	105.00	0.143	15.02		
Starch	Short Ton	260.00	0.011	2.86		
Cryolite	Short Ton	493.90	0.035		17.29	
Aluminum Fluoride	Short Ton	514.50	0.02		10.29	
Water				1.68		
Maintenance Materials 1.5% of C.I.				13.00		
Maintenance Materials 2.5% of C.I.					107.33	
Maintenance (OTEC) 2.5% of C.I.					55.02	
Cathode Materials	Short Ton	36.00	1.00		36.00	
				<u>188.55</u>	<u>225.93</u>	414.48
Purchased Fuel	10 ⁶ BTU	4.00	22.12	88.48		
Purchased Fuel	10 ⁶ BTU	4.00	6.60		26.40	
Calcined Coke	Short Ton	120.00	0.42		50.40	
Pitch	Short Ton	103.00	0.15		15.45	
				<u>88.48</u>	<u>92.25</u>	180.73
Labor	MH	12.75	3.19	40.67		
Labor	MH	12.75	8.00		102.00	
Labor (OTEC)	MH	24.75	2.79		69.08	
Plant Overhead (45% of Wages)				18.30	76.99	
Local Taxes & Insurance 2% of C.I.				17.33	129.88	
				<u>76.30</u>	<u>377.95</u>	454.25
Subtotal						1,049.46
<u>Energy</u>						
Electric Power (10% Bayer)	kWhr	0.10	53.10	5.31		
Electric Power (10% Hall)	Kwhr	0.10	1118.0		111.80	
				<u>5.31</u>	<u>111.80</u>	117.11

CASE B3

ESTIMATED COSTS FOR A BAYER-DRAINED CATHODE PLANT ($j = 7 \text{ kA/m}^2$) ON MINDANAO,
 POWERED BY OTEC THROUGH CABLE $\Delta T = 24^\circ\text{C}$; 3 mile cable
 Annual Capacity: 356,837 MT/yr (1980 U.S. \$)

CAPITAL COSTS	\$ x 10 ⁶	Total
Cost of Bayer Plant	340.85	
Cost of Drained Cathode Hall Plant (See Table V-B)	1,089.19	
Cost of OTEC Plant, 510 MW @ \$1730.8	882.71	
TOTAL CAPITAL COST		2,312.75
Cost of Land	23.60	
Cost of Offices	5.70	
CAPITAL COST FOR INVESTMENT TAX CREDIT*		2,283.45
Capital Cost for Solar Energy*	882.71	
Investment Tax Credit		

*Investment tax credits not applicable to Philippine corporate taxes.

PRODUCTION COSTS	Unit	\$/Unit	# of Units	\$ Per Short Ton		
			Per Short Ton of Aluminum	of Aluminum		
				Bayer	Hall + OTEC	Total
<u>Raw Materials and Other</u>						
Bauxite	Short Ton	33.80	4.56	154.13		
Limestone	Short Ton	7.35	0.253	1.86		
Soda Ash	Short Ton	105.00	0.143	15.02		
Starch	Short Ton	260.00	0.011	2.86		
Cryolite	Short Ton	493.90	0.035		17.29	
Aluminum Fluoride	Short Ton	514.50	0.02		10.29	
Water				1.68		
Maintenance Materials	1.5% of C.I.			13.00		
Maintenance Materials	2.5% of C.I.				69.25	
Maintenance (OTEC)	2.5% of C.I.				56.12	
Cathode Materials	Short Ton	36.00	1.00		36.00	
				<u>188.55</u>	<u>188.95</u>	377.50
Purchased Fuel	10 ⁶ BTU	4.00	22.12	88.48		
Purchased Fuel	10 ⁶ BTU	4.00	6.60		26.40	
Calcined Coke	Short Ton	120.00	0.42		50.40	
Pitch	Short Ton	103.00	0.15		15.45	
				<u>88.48</u>	<u>92.25</u>	180.73
Labor	MH	12.75	3.19	40.67		
Labor	MH	12.75	8.00		102.00	
Labor (OTEC)	MH	24.75	2.79		69.08	
Plant Overhead (45% of Wages)				4.37	42.03	
Local Taxes & Insurance	2% of C.I.			17.33	100.29	
				<u>31.40</u>	<u>235.72</u>	267.12
Subtotal						<u>825.35</u>
<u>Energy</u>						
Electric Power (10% Bayer)	kWhr	0.02	53.10	1.06		
Electric Power (10% Hall)	Kwhr	0.02	1118.0		22.36	
				<u>1.06</u>	<u>22.36</u>	23.42

CASE B - COMMENTS

(a) BREAKDOWN OF CAPITAL COSTS FOR A BAYER-DRAINED CATHODE HALL PLANT

	\$ x 10 ⁶	Total
Alumina and Carbon Storage	23.79	
Mobile Equipment	3.66	
Carbon Paste Plant	17.39	
Green Carbon Plant	66.81	
Carbon Baking Plant	86.95	
Carbon Rodding Plant	50.33	
Substation	10.98	
Rectifiers	62.23	
Potlines, 1300 Cells @ \$177 K/cell	230.10	
Busbars	80.53	
Structures and Ventilation	226.65	
Metal Casting	56.74	
Utilities Excluding Power Plant	43.93	
Support Facilities and Pollution Control	139.10	
Total Cost for Gulf Coast U.S.A.		<u>1,089.19</u>

Capital costs for the plant were extrapolated linearly from Table 3-4, except that cell cost was increased by \$50K. The number of cells for $j = 7.0 \text{ kA/m}^2$ was adjusted to 1300 units, with a corresponding change in the scaling for the item relating to structures and ventilation.

- (b) For Guam, it is assumed that 55% of the work would be performed on the island with a geographic cost index of 2.0, and that 45% of the cost represents equipment that would be fabricated elsewhere and shipped in for installation. The estimated cost of the drained cathode Hall cell reduction plant on Guam is \$1,688.24 million.

Because of the lack of fossil fuels on Guam, it was assumed that the Bayer plant was located at some other location, where the geographic location index was 1.0 and our other energy inputs for the Bayer process would be the same as for a U.S.A location.

CASE C1

ESTIMATED COSTS FOR AN ALUMINUM COMPLEX BAYER PLANT ON SHORE AND DRAINED CATHODE
CELLS ($j = 14.0 \text{ kA/m}^2$) ON OTEC PLATFORM OFF U. S. GULF COAST $\Delta T = 20^\circ\text{C}$
Annual Capacity: 311,093 MT/yr (1980 U.S. \$)

CAPITAL COSTS	Units	No. Required	\$ Unit	\$x10 ⁶	Total
OTEC Power System	kW	5 x 10 ⁵	2,102.5	1,051.25	
Add'l Cost. for 100 MW _e Units	kW	5 x 10 ⁵	426.9	213.45	
Gas Turbines 100 MW _e	each	5	38.16 x 10 ⁶	190.80	
					1,455.50
Hull Cost	each	5	89.23 x 10 ⁶	466.15	
Drained Cathode Potroom	each	5	65.35 x 10 ⁶	326.77	
					772.92
Bayer Plant				328.20	
Shore Carbon Plant and Handling Facilities				293.45	
Subtotal					621.65
TOTAL CAPITAL COST					2,850.07
Cost of Land				23.60	
Cost of Offices				5.70	
Cost for Investment Tax Credit					2,820.77
Cost for Solar Energy Tax Credit					2,228.42

PRODUCTION COSTS	Unit	\$/Unit	# of Units Per Short Ton of Aluminum	\$ Per Short Ton of Aluminum Hall + Bayer OTEC	Total
<u>Raw Materials and Other</u>					
Bauxite	Short Ton	33.80	4.56	154.13	
Limestone	Short Ton	7.35	0.253	1.86	
Soda Ash	Short Ton	105.00	0.143	15.02	
Starch	Short Ton	260.00	0.011	2.86	
Cryolite	Short Ton	493.90	0.035	17.29	
Aluminum Fluoride	Short Ton	514.50	0.02	10.29	
Water				1.68	
Maintenance Materials 1.5% of C.I. (Bayer)				14.36	
Maintenance Materials 2.5% of C.I. (Hall)				45.23	
Maintenance (OTEC)	2.5% of C.I.			138.68	
Cathode Materials	Short Ton	36.00	1.00	36.00	
				189.91	437.40
Purchased Fuel	10 ⁶ BTU	4.00	22.12	88.48	
Purchased Fuel	10 ⁶ BTU	4.00	6.60	26.40	
Calcined Coke	Short Ton	120.00	0.42	50.40	
Pitch	Short Ton	103.00	0.15	15.45	
				88.48	180.73
Labor	MH	14.50	3.19	46.26	
Labor	MH	14.50	4.50	65.25	
Labor (OTEC)	MH	24.75	6.76	164.48	
Plant Overhead (45% of Wages)				20.82	103.38
Transportation	Short Ton	15.00	1.00	15.00	
Local Taxes & Insurance 2% of C.I.				19.14	147.12
				86.22	581.45
Total					1189.58

CASE C2

ESTIMATED COSTS FOR AN ALUMINUM COMPLEX BAYER PLANT ON SHORE AND
DRAINED CATHODE CELLS ($j = 14.0 \text{ kA/m}^2$) ON OTEC PLATFORM AT GUAM $\Delta T = 24^\circ\text{C}$
Annual Capacity: 311,093 MT/hr
(1980 U.S. \$)

CAPITAL COSTS	Units	No. Required	\$/Unit	\$X10 ⁶	Total
OTEC Power System	kw	5×10^5	1,445.6	722.80	
Add'l Cost for 100 MWe Units	kw	5×10^5	426.9	213.45	
Gas Turbines 100 MWe	each	5	38.16×10^6	190.80	1,127.05
Hull Cost	each	5	89.23×10^6	466.15	
Drained Cathode Potroom and Cells	each	5	65.35×10^6	326.77	772.92
Bayer Plant				328.20	
Shore Carbon Plant and Handling Facilities				454.85	
Subtotal					783.05
TOTAL CAPITAL COST					2,693.02
Cost of Land				23.60	
Cost of Offices				5.70	
Cost for Investment Tax Credit					2,653.72
Cost for Solar Energy Tax Credit					1,899.97

PRODUCTION COSTS	Unit	\$/Unit	# of Units Per Short Ton of Aluminum	\$ Per Short Ton of Aluminum	Bayer	Hall	Total
<u>Raw Materials and Other</u>							
Bauxite	Short Ton	33.80	4.56	154.13			
Limestone	Short Ton	7.35	0.253	1.86			
Soda Ash	Short Ton	105.00	0.143	15.02			
Starch	Short Ton	260.00	0.011	2.86			
Cryolite	Short Ton	493.90	0.035			17.29	
Aluminum Fluoride	Short Ton	514.90	0.02			10.29	
Water				1.68			
Maintenance Materials (Bayer)	1.5% of C.I.			14.36			
Maintenance Materials (Hall)	2.5% of C.I.					57.00	
Maintenance (OTEC)	2.5% of C.I.					114.72	
Cathode Materials	Short Ton	36.00	1.00			36.00	
					189.91	235.30	425.21
Purchased Fuel	10^6 BTU	4.00	22.12	88.48			
Purchased Fuel	10^6 BTU	4.00	6.60			26.40	
Calcined Coke		120.00	0.42			50.40	
Pitch		103.00	0.15			15.45	
					88.48	92.25	180.73
Labor	MH	12.75	3.19	40.67			
Labor	MH	12.75	4.50			57.38	
Labor (OTEC)	MH	24.75	6.70			167.40	
Plant Overhead (45% of wages)				18.30		101.15	
Transportation	Short Ton	15.00	1.00			15.00	
Local Taxes & Insurance	2% of C.I.			19.15		137.38	
					78.12	478.31	556.43
Total							1162.37

CASE C - COMMENTS

For Case C1, we assumed that the Bayer plant, the carbon plant, and the cast house would be located on the shore, with the drained cathode reduction plant on the OTEC platform as discussed in Section 2.4. The costs for the reduction plant given in Table 3.4 were modified to delete the entries for the substation, rectifiers, potlines, busbars, and structures and ventilation. In addition, one-half the amount for support facilities and pollution control was deleted. The remaining costs were then scaled as the mass flow to the 0.7 power and then escalated from 1979 to mid 1980, using the Chemical Engineering Index.

For the plantship, we have estimated the cost for the drained cathode cell and the supporting systems which scale linearly with the number of cells. The number of switching systems and rectifiers will depend upon the assumed number of plantships (five). An additional 18% was added to MITRE OTEC Cost Forecast Tree costs to account for the fact that five 100 MWe plantships would be built in place of the 400 MWe plant which was the cost estimate baseline. The costs are summarized in Table A.

TABLE A. DETAILS OF CAPITAL COSTS FOR AN ALUMINUM COMPLEX BAYER PLANT ON SHORE AND DRAINED CATHODE CELLS ON OTEC PLATFORM OFF U.S. GULF COAST, CASE C1

	\$ x 10 ⁶	Total
<u>Shore Carbon Plant and Handling Facilities</u>		
Alumina and Carbon Storage	16.72	
Mobile Equipment	2.57	
Carbon Paste Plant	12.22	
Green Carbon Plant	46.94	
Carbon Baking Plant	61.08	
Carbon Rodding Plant	35.36	
Metal Casting	39.86	
Utilities Excluding Power Plant	30.86	
Support Facilities	<u>47.84</u>	
		293.45
<u>Drained Cathode Cells and Power Units</u>		
Reduction Cells	550 @ \$ 150 x 10 ³ /cell	82.50
Switching	5 @ \$ 4 x 10 ⁶ /ship	20.00
Rectifiers	5 @ \$ 22.9 x 10 ⁶ /ship	114.50
Busbars	550 @ \$42.78 x 10 ³ /cell	23.53
Structures and Ventilation	550 @ \$156.8 x 10 ³ /cell	<u>86.24</u>
		326.77

The OTEC maintenance material cost was estimated as 2-1/2% of capital investment. The OTEC power system operators and maintenance personnel, the reduction plant operation and maintenance personnel, and the hotel staff personnel, as per the plantship manning schedule, Table B, were included under the item, "Additional OTEC Labor."

Because of shortage of fuel on Guam, the Bayer plant for Case C2 was assumed to be constructed in Australia where the geographic cost index is 1.0. Cost of shipping from Australia to Guam is small and was not included.

The capital cost for the plantship was adjusted to the larger sized hull required for the drained cathode Hall cell plant layout.

TABLE B. MANPOWER REQUIREMENTS FOR FIVE 100 MW_e OTEC
DRAINED CATHODE REDUCTION PLANTSHIPS, CASES C1 and C2

	Per Shift	Per Crew	Per Case
A. POWER STATION CREW			
Master	--	1	5
Mates	--	2	10
Chief Engineer	--	1	5
Chief Diver	--	1	5
Shift Foreman	1	2	10
Control Room Operators	1	4	20
Roving Operators/Divers	2	4	20
Mechanics/Pipe Fitters	2	4	20
Electronic/Instrumentation Engineer	3	6	30
Mechanics/Welders	2	4	20
Power Station Total		<u>27</u>	<u>135</u>
B. REDUCTION PLANT			
Tour Foreman	--	1	5
Safety	--	1	5
Laboratory	--	3	15
Supervision	2	4	20
Maintenance/Mechanical	5	10	50
Maintenance/Electrical/Instrumentation	5	10	50
Portroom Operation (20 Cells/Operator)	5	10	50
Pelletizing	1	2	10
Fume Control	1	2	10
Loading/Unloading	--	10	50
Reduction Plant Total		<u>51</u>	<u>255</u>
C. HOTEL STAFF			
Chief Steward	--	1	5
Doctor/2 Medical Technicians	--	3	15
Cooks/Bakers	3	6	30
Utilitymen (Stewards, Galley, Laundry)	9	18	90
Hotel Staff Total		<u>28</u>	<u>140</u>
CREW TOTAL		100	530

$$\frac{530 \text{ People} \times 84 \text{ hrs/wk} \times 52 \text{ wks/yr}}{311,093 \text{ MT/yr}} = 7.44 \text{ MH/MT}$$

CASE D1

ESTIMATED COSTS FOR A TOTH PROCESS AlCl_3 -CHLORIDE REDUCTION PLANT LOCATED ON
 U.S. GULF COAST, POWERED BY OTEC THROUGH 100 MILE CABLE $\Delta T = 20^\circ\text{C}$
 Annual Capacity: 362,700 MT/yr
 (1980 U.S. \$)

CAPITAL COSTS	\$ x 10 ⁶	Total
Cost of Toth Plant(a)	337.93	
Cost of Chloride Reduction Plant(b)	545.97	
Cost of OTEC Plant, 510 MW @ \$2649/kW	<u>1,351.13</u>	
TOTAL COST		2,235.03
Cost of Land	23.60	
Cost of Offices	<u>5.70</u>	
CAPITAL COST FOR INVESTMENT TAX CREDIT		2,205.73
Cost for Solar Energy Investment Tax Credit	1,351.13	

PRODUCTION COSTS	Unit	\$/Unit	# of Units Per Short Ton of Aluminum	\$ Per Short Ton of Aluminum	Total
<u>Raw Materials</u>					
Clay (Kaolin)	Short Ton	10.00	5.79	57.90	
Chlorine	Short Ton	150.00	0.08	12.00	
Oxygen	Short Ton	20.00	1.47	29.40	
NaCl	Short Ton	30.00	0.001	0.03	
LiCl	Short Ton	2000.00	0.001	2.00	
Coal	10 ⁶ BTU	1.50	16.31	24.47	
Coke	Short Ton	50.00	1.24	62.00	
Water	10 ³ Gal	0.50	1.54	0.77	
Water (Cooling)	10 ³ Gal	0.05	140.00	7.00	
Other Operating Supplies				<u>16.47</u>	
					212.31
<u>Labor and Other</u>					
Direct Operating Labor	MH	14.50	5.56	80.62	
Maintenance Labor	MH	14.50	7.62	110.49	
OTEC Labor	MH	24.75	2.79(c)	69.08	
Plant Overhead (45% of Wages & Fringe)				117.09	
Maintenance Materials	2.5% of C.I.			139.08	
Local Taxes & Insurance	2% of C.I.			<u>111.84</u>	
					628.92
Total					<u>841.23</u>

CASE D2

ESTIMATED COSTS FOR A TOTH-CHLORIDE PLANT LOCATED ON GUAM,
POWERED BY OTEC THROUGH CABLE
 $\Delta T = 24^{\circ}\text{C}$; 3 mile cable; Annual Capacity: 362,700 MT/yr
(1980 U. S. \$)

CAPITAL COSTS	\$ x 10 ⁶	Total
Cost of Toth Plant(d)	523.80	
Cost of Chloride Reduction Plant(e)	846.25	
Cost of OTEC Plant, 510 MW @ \$1730/kw	882.71	
TOTAL COST		2,252.76
Cost of Land	23.60	
Cost of Offices	5.70	
CAPITAL COST FOR INVESTMENT TAX CREDIT		2,223.46
Cost for Solar Energy Investment Tax Credit	882.71	

PRODUCTION COSTS	Unit	\$/Unit	# of Units Per Short Ton of Aluminum	\$ Per Short Ton of Aluminum	Total
<u>Raw Materials(f)</u>					
Clay (Kaolin)	Short Ton	10.00	5.79	57.90	
Chlorine	Short Ton	150.00	0.08	12.00	
Oxygen	Short Ton	20.00	1.47	29.40	
NaCl	Short Ton	30.00	0.001	0.03	
LiCl	Short Ton	2000.00	0.001	2.00	
Coal	10 ⁶ BTU	1.50	16.31	24.47	
Coke	Short Ton	50.00	1.24	62.00	
Water	10 ³ Gal	0.50	1.54	0.77	
Water (Cooling)	10 ³ Gas	0.05	140.00	7.00	
Other Operating Supplies				16.47	
					212.31
<u>Labor and Other</u>					
Direct Operating Labor	MH	12.75(g)	5.56	70.89	
Maintenance Labor	MH	13.2	7.62	100.58	
OTEC Labor	MH		24.75 (c)	2.79	69.08
Plant Overhead (45% of Wages & Fringe)					108.25
Maintenance Materials	2.5% of C.I.				140.90
Local Taxes & Insurance	2% of C.I.				112.72
					602.42
Total					814.73

CASE D3

ESTIMATED COSTS FOR A TOTH PROCESS $AlCl_3$ PRODUCTION PLANT-CHLORIDE REDUCTION
 PLANT, POWERED BY OTEC THROUGH 3 MILE CABLE ON MINDANAO;
 $\Delta T = 24^\circ C$; Annual Capacity: 362,700 MT/yr
 (1980 U. S. \$)

	\$ x 10 ⁶	Total
Cost of Toth Plant	337.93	
Cost of Chloride Reduction Plant	545.97	
Cost of OTEC Plant	882.71	
TOTAL COST		1,776.61
Cost of Land	23.60	
Cost of Offices	5.70	
CAPITAL COST FOR INVESTMENT TAX CREDIT*		1,737.31
Cost for Solar Energy Investment* Tax Credit	882.71	

* Investment tax credits not applicable to Philippine corporate taxes.

PRODUCTION COSTS	Unit	\$/Unit	# of Units Per Short Ton of Aluminum	\$ Per Short Ton of Aluminum	Total
<u>Raw Materials^(f)</u>					
Clay (Kaolin)	Short Ton	10.00	5.79	57.90	
Chlorine	Short Ton	150.00	0.08	12.00	
Oxygen	Short Ton	20.00	1.47	29.40	
NaCl	Short Ton	30.00	0.001	0.03	
LiCl	Short Ton	2000.00	0.001	2.00	
Coal	10 ⁶ BTU	1.50	16.31	24.47	
Coke	Short Ton	50.00	1.24	62.00	
Water	10 ³ Gal	0.50	1.54	0.77	
Water (Cooling)	10 ³ Gas	0.05	140.00	7.00	
Other Operating Supplies				16.47	
					212.31
<u>Labor and Other</u>					
Direct Operating Labor	MH	3.04 ^(h)	5.56	16.90	
Maintenance Labor	MH	3.04	7.62	23.16	
OTEC Labor	MH	24.75	2.79 ^(c)	69.08	
Plant Overhead				110.50	
(45% of Wages & Fringe)					
Maintenance Materials	2.5% of C.I.			88.39	
Local Taxes & Insurance	2.0% of C.I.				
					357.14
Total					569.45

CASE D4

ESTIMATED AND PRODUCTION COSTS FOR A TOTH PROCESS AlCl_3 PRODUCTION
 PLANT-CHLORIDE PLANT LOCATED ON PUERTO RICO, POWERED BY OTEC
 THROUGH 3 MILE CABLE $\Delta T = 22^\circ\text{C}$
 Annual Capacity: 362,700 MT/yr (1980 U. S. \$)

CAPITAL COSTS		\$ x 10 ⁶	Total	
Cost of Toth Plant		412.27		
Cost of Chloride Reduction Plant		666.08		
Cost of OTEC Plant, 510 MW @ \$1940/kw		989.40		
TOTAL COST			2,067.75	
Cost of Land		23.60		
Cost of Offices		5.70		
CAPITAL COST FOR INVESTMENT TAX CREDIT*		N.A.		
Cost for Solar Energy Investment*		N.A.		
Tax Credit				

PRODUCTION COSTS	Unit	\$/Unit	# of Units Per Short Ton of Aluminum	\$ Per Short Ton of Aluminum	Total
<u>Raw Materials</u>					
Clay (Kaolin)	Short Ton	10.00	5.79	57.90	
Chlorine	Short Ton	150.00	0.08	12.00	
Oxygen	Short Ton	20.00	1.47	29.40	
NaCl	Short Ton	30.00	0.001	0.03	
LiCl	Short Ton	2000.00	0.001	2.00	
Coal	10 ⁶ BTU	1.50	16.31	24.47	
Coke	Short Ton	50.00	1.24	62.00	
Water	10 ³ Gal	0.50	1.54	0.77	
Water (Cooling)	10 ³ Gas	0.05	140.00	7.00	
Other Operating Supplies				16.47	
					212.31
<u>Labor and Other</u>					
Direct Operating Labor		MH	9.00	5.56	50.04
Maintenance Labor	MH	9.00	7.62	68.58	
OTEC Labor	MH	24.75	2.79	69.08	
Plant Overhead				84.47	
(45% of Wages & Fringe)					
Maintenance Materials	2.5% of C.I.			129.23	
Local Taxes & Insurance	2.0% of C.I.			103.38	
					504.78
Total					717.09

CASE D5

ESTIMATED CAPITAL AND PRODUCTION COSTS FOR A TOTH PROCESS AlCl_3 PRODUCTION
 PLANT-CHLORIDE REDUCTION PLANT LOCATED ON VIRGIN ISLANDS, POWERED BY OTEC
 THROUGH 3 MILE CABLE $\Delta T = 22^\circ\text{C}$; Annual Capacity: 362,700 MT/yr
 (1980 U. S. \$)

			\$ x 10 ⁶	Total
Cost of Toth Plant			393.86	
Cost of Chloride Reduction Plant			636.33	
Cost of OTEC Plant, 510 MW @ \$1940/kw			<u>989.40</u>	
TOTAL COST				2,019.59
Cost of Land			23.60	
Cost of Offices			5.70	
CAPITAL COST FOR INVESTMENT TAX CREDIT				
Cost for Solar Energy Investment				
Tax Credit				

PRODUCTION COSTS	Unit	\$/Unit	# of Units Per Short Ton of Aluminum	\$ Per Short Ton of Aluminum	Total
<u>Raw Materials</u>					
Clay (Kaolin)	Short Ton	10.00	5.79	57.90	
Chlorine	Short Ton	150.00	0.08	12.00	
Oxygen	Short Ton	20.00	1.47	29.40	
NaCl	Short Ton	30.00	0.001	0.03	
LiCl	Short Ton	2000.00	0.001	2.00	
Coal	10 ⁶ BTU	1.50	16.31	24.47	
Coke	Short Ton	50.00	1.24	62.00	
Water	10 ³ Gal	0.50	1.54	0.77	
Water (Cooling)	10 ³ Gas	0.05	140.00	7.00	
Other Operating Supplies				<u>16.47</u>	
					212.3
<u>Labor and Other</u>					
Direct Operating Labor	MH	7.25	5.56	40.31	
Maintenance Labor	MH	7.25	7.62	55.25	
OTEC Labor	MH	24.75	2.79	68.05	
Plant Overhead				74.08	
(45% of Wages & Fringe)					
Maintenance Materials 2.5% of C.I.				126.22	
Local Taxes & Insurance 2.0% of C.I.				<u>100.98</u>	
					464.8
Total					677.2

CASE D COMMENTS

- (a) The estimated cost of the Toth chlorination plant was obtained from Reference 36, as $\$232.6 \times 10^6$ in 1975, and scaled using the Chemical Engineering Plant Cost Index to 1980.

- (b) BREAKDOWN OF CAPITAL COSTS FOR SHORE BASE CHLORIDE REDUCTION PLANT

	\$ x 10 ⁶	Total
AlCl ₃ Storage	24.18	
Mobile Equipment	3.72	
Cell Repair Facility	55.36	
Substation & Rectifiers	59.52	
Cell Stack Assemblies (100 Units)	55.36	
Busbars	45.40	
Structures & Ventilation	17.44	
Metal Casting	57.66	
Utilities Excluding Power Plant	44.64	
Electrolyte Recycle	41.52	
Chlorine Recycle	71.97	
Support Facilities	69.20	
Total Estimated Cost for U.S.A.		545.97

- (c) Table C gives the Manpower requirements for a 500 MWe OTEC plantship.

TABLE C. MANPOWER REQUIREMENTS FOR 500 MWe OTEC PLANTSHIP

	Per Shift	Per Crew
A. POWER STATION CREW		
Master	--	1
Mates	--	2
Chief Engineer	--	1
Chief Diver	--	1
Shift Foreman	1	2
Control Room Operators	1	2
Roving Operators/Divers	10	20
Mechanics/Pipe Fitters	10	20
Electronic/Instrumentation Engineer	15	30
Mechanics/Welders	10	20
Power Station Total		99
B. HOTEL STAFF		
Chief Steward	--	1
Doctor/2 Medical Technicians	--	3
Cooks/Bakers	3	6
Utilitymen (Stewards, Galley, Laundry)	9	18
Hotel Staff Total		28
CREW TOTAL		127

$$\frac{127 \text{ People} \times 8760 \text{ hr/yr}}{362,700 \text{ MT/yr}} = 3.07 \text{ MH/MT} = 2.79 \text{ MH/ton}$$

- (d) For the Toth plant on Guam, Case D2, the geographic index for Guam was applied to 55% of the cost given in Case 1.
- (e) In case D1 the capital cost estimate for a chloride reduction plant in the U.S. was estimated as \$545.97M. The capital costs for location of the plant on Guam adjusted by assuming that 55% of the costs would be increased by the geographic location index of 2.0, the remainder of the plant represents fabricated equipment and machinery which would have a geographic location index of 1.00.
- (f) It is assumed that backup electrical power from the Guam utility grid will not be required for a chloride reduction plant in any great quantities because of the supposed ease with which the chloride process plant can be shut down. For Guam, the wage rate for a skilled worker is \$8.40/hr. Adding 15% for supervision and 32% for fringe benefits, the projected labor cost per hour (mid 1980) is \$12.75.
- (h) For the Philippine Islands, the wage rate for a skilled worker was assumed as \$2.00 per hour. Adding 15% for supervision and 32% for fringe benefits, the projected labor cost per hour (mid 1980) is \$3.04.

CASE E1.1

ESTIMATED COSTS FOR FIVE 100 MWe FLOATING OTEC CHLORIDE REDUCTION PLANTS
AND A TOTTH CHLORINATION PLANT ON U.S. GULF COAST;
Annual Capacity: 362,700 MT/yr (1980 U. S. \$)

CAPITAL COSTS		\$ x 10 ⁶	Total		
Cost of Toth Plant(a)		337.93			
Cost of the Shore Support Facility(b)		293.50			
Cost of Barge Transportation with Storage(b)		43.92			
Cost of Chloride Reduction Plants(b)		383.65			
Cost of OTEC Power Systems 5 Units @ 102 MWe @ \$2798.3/kw		1,427.13			
			2,486.13		
Cost of Land		23.60			
Cost of Offices		5.70			
CAPITAL COST FOR INVESTMENT TAX CREDIT			2,456.83		
CAPITAL COST FOR SOLAR ENERGY CREDIT		1,854.70			

PRODUCTION COSTS			# of Units Per Short Ton of Aluminum	\$ Per Short Ton of Aluminum		Total
Raw Materials	Units	\$/Unit		Toth(c)	Shore OTEC	
Clay	Short Ton	10.00	5.70	57.00		
Chlorine	Short Ton	150.00	0.076	11.40		
Oxygen	Short Ton	20.00	1.47	29.40		
Water	l.s.			1.41		
Coke (Green)	Short Ton	50.00	1.22	60.80		
Purchased Fuel (Toth)	MBTU	5.00	16.10	80.50		
Purchased Fuel Remelt	MBTU	5.00	2.5		12.50	
Maintenance (Toth)	2.5% of C.I.			21.14		
Maintenance (Reduction & Transport)	3% of C.I.				32.09	
Maintenance (Shore)	1.5% of C.I.				11.01	
Maintenance (OTEC)	2.5% of C.I.				89.26	
				261.65	144.86	406.51
Electricity	kWhr	0.03	333.0	9.99		
<u>Labor</u>						
Toth	MH	14.50	5.27	76.42		
Shore Base	MH	14.50	3.19(e)		46.26	
OTEC	MH	22.50	6.00(d)		135.00	
Plant Overhead (45% of wages)				34.39	81.57	
Tug Cost	Day	5,000.00	2.0		10.60	
Taxes & Insurance	2% of C.I.			16.91	107.49	
				127.72	380.92	508.64
Total						915.15

CASE E1.2

ESTIMATED COSTS FOR TWO 400 MWe FLOATING OTEC CHLORIDE REDUCTION PLANTS IN
 GULF OF MEXICO SUPPORTED BY TOTTH CHLORINATION PLANT ON U.S. GULF COAST
 $\Delta T = 20^{\circ}\text{C}$ Annual Capacity: 580,320 MT/yr
 (1980 U. S. \$)

CAPITAL COSTS			\$ x 10 ⁶	Total		
Cost of Toth Plant(f)			469.58			
Cost of the Shore Support Facility			407.84			
Cost of Barge Transportation with Storage			70.27			
Cost of Chloride Reduction Plants			613.84			
Cost of OTEC Power Systems 2 Units @ 400 MWe @ \$2798.3/kw			2,238.64	3,800.17		
Cost of Land			23.60			
Cost of Offices			20.00			
CAPITAL COST FOR INVESTMENT TAX CREDIT				3,770.87		
Cost for Solar Energy Investment Tax Credit			2,922.75			

PRODUCTION COSTS			# of Units Per Short Ton of Aluminum	\$ Per Short Ton of Aluminum		
Raw Materials	Unit	\$/Unit		Toth	Shore & OTEC	Total
Clay	Short Ton	10.00	5.70	57.00		
Chlorine	Short Ton	150.00	0.076	11.40		
Oxygen	Short Ton	20.00	1.47	29.40		
Water	l.s.			1.41		
Coke (Green)	Short Ton	50.00	1.22	60.80		
Purchased Fuel (Toth)	MBTU	5.00	16.10	80.50		
Purchased Fuel Remelt	MBTU	5.00	2.5		12.50	
Maintenance (Toth)	2.5% of C.I.			18.36		
Maintenance (Reduction & Transport)	3% of C.I.				32.09	
Maintenance (Shore)	1.5% of C.I.				9.57	
Maintenance (OTEC)	2.5% of C.I.				87.51	
				258.87	141.67	400.54
Electricity	kWhr	0.03	333.0	9.99		
<u>Labor</u>						
Toth	MH	14.50	5.27	76.42		
Shore Base	MH	14.50	3.19		46.26	
OTEC	MH	22.50	3.94(d)		89.65	
Plant Overhead (45% of wages)				34.39	60.71	
Tug Cost	Day	5,000.00	2.0		10.60	
Taxes & Insurance	2% of C.I.			14.69	104.16	
				125.50	310.38	435.88
Total						836.42

CASE E2

ESTIMATED COSTS FOR FIVE 100 MWe FLOATING OTEC CHLORIDE REDUCTION PLANTS
AND A TOTH CHLORINATION PLANT ON GUAM $\Delta T = 24^{\circ}\text{C}$ Annual Capacity: 362,700 MT/yr
(1980 U. S. \$)

CAPITAL COSTS	\$ x 10 ⁶	Total
Cost of Toth Plant	523.79	
Cost of the Shore Support Facility	454.93	
Cost of Barge Transportation with Storage	43.92	
Cost of Chloride Reduction Plants	383.65	
Cost of OTEC Power Systems 5 Units @ 102 MWe @ \$2798.3/kW	1,037.85	
		2,444.14
Cost of Land	23.60	
Cost of Offices	5.70	
CAPITAL COST FOR INVESTMENT TAX CREDIT		2,473.44
Cost for Solar Energy Investment Tax Credit	1,465.42	

PRODUCTION COSTS	Unit	\$/Unit	# of Units Per Short Ton of Aluminum	\$ Per Short Ton of Aluminum		
				Toth	Shore & OTEC	Total
Raw Materials						
Clay	Short Ton	10.00	5.70	57.00		
Chlorine	Short Ton	150.00	0.076	11.40		
Oxygen	Short Ton	20.00	1.47	29.40		
Water	l.s.			1.41		
Coke (Green)	Short Ton	50.00	1.22	60.80		
Purchased Fuel (Toth)	MBTU	5.00	16.10	80.50		
Purchased Fuel Remelt	MBTU	5.00	2.5		12.50	
Maintenance (Toth)	2.5% of C.I.			32.76		
Maintenance (Reduction & Transport)	3% of C.I.				32.09	
Maintenance (Shore)	1.5% of C.I.				17.07	
Maintenance (OTEC)	2.5% of C.I.				67.03	
				273.27	128.69	401.96
Electricity	kWhr	0.10	333.0	33.30		
<u>Labor</u>						
Toth	MH	7.59	5.27	40.00		
Shore Base	MH	7.59	3.19		24.21	
OTEC	MH	22.50	6.00		135.00	
Plant Overhead (45% of wages)				18.00	71.65	
Tug Cost	Day	5,000.00	2.0		10.60	
Taxes & Insurance	2% of C.I.			26.21	96.09	
				84.21	337.55	421.76
Total						823.72

CASE E3

ESTIMATED COSTS FOR FIVE 100 MWe FLOATING OTEC CHLORIDE REDUCTION PLANTS AND
 TOTH CHLORINATION PLANT ON MINDANAO $\Delta T = 24^{\circ}\text{C}$;
 Annual Capacity: 362,700 MT/yr
 (1980 U. S. \$)

CAPITAL COSTS		\$ x 10 ⁶	Total
Cost of Toth Plant		337.93	
Cost of the Shore Support Facility		293.50	
Cost of Barge Transportation with Storage		43.92	
Cost of Chloride Reduction Plants		383.65	
Cost of OTEC Power Systems 5 Units @ 102 MWe @ \$2798.3/kw		1,033.78	2,092.78
Cost of Land		23.60	
Cost of Offices		20.00	
CAPITAL COST FOR INVESTMENT TAX CREDIT			2,063.48
Cost for Solar Energy Investment Tax Credit		1,461.35	

PRODUCTION COSTS				\$ Per Short Ton of Aluminum		
Raw Materials	Unit	\$/Unit	# of Units Per Short Ton of Aluminum	Toth	Shore & OTEC	Total
Clay	Short Ton	10.00	5.70	57.00		
Chlorine	Short Ton	150.00	0.076	11.40		
Oxygen	Short Ton	20.00	1.47	29.40		
Water	l.s.			1.41		
Coke (Green)	Short Ton	50.00	1.22	60.80		
Purchased Fuel (Toth)	MBTU	5.00	16.10	80.50		
Purchased Fuel Remelt	MBTU	5.00	2.5		12.50	
Maintenance (Toth)	2.5% of C.I.			21.14		
Maintenance (Reduction & Transport)	3% of C.I.				32.09	
Maintenance (Shore)	1.5% of C.I.				11.09	
Maintenance (OTEC)	2.5% of C.I.				64.66	
				261.65	120.26	381.91
Electricity	kWhr	0.03	333.0	9.99		
<u>Labor</u>						
Toth	MH	3.04	5.27	16.02		
Shore Base	MH	3.04	3.19		9.70	
OTEC	MH	24.75	5.45		135.00	
Plant Overhead (45% of wages)				7.21	65.12	
Tug Cost	Day	5,000.00	1.0		5.00	
Taxes & Insurance	2% of C.I.			16.91	87.81	
				40.16	302.63	342.77
Total						724.68

CASE E4

ESTIMATED COSTS FOR FIVE 100 MWe FLOATING OTEC CHLORIDE REDUCTION PLANTS AND
 TOTTH CHLORINATION PLANT ON PUERTO RICO
 $\Delta T = 22^{\circ}\text{C}$; Annual Capacity: 400,000 ST/yr
 (1980 U. S. \$)

CAPITAL COSTS		\$ x 10 ⁶	Total			
Cost of Toth Plant		412.27				
Cost of the Shore Support Facility		358.07				
Cost of Barge Transportation with Storage		43.92				
Cost of Chloride Reduction Plants		383.65				
Cost of OTEC Power Systems 5 Units @ 102 MWe @ \$2798.3/kw		1,167.50				
			2,365.41			
Cost of Land		23.60				
Cost of Offices		20.00				
CAPITAL COST FOR INVESTMENT TAX CREDIT						
Cost for Solar Energy Investment Tax Credit						
PRODUCTION COSTS						
Raw Materials	Unit	\$/Unit	# of Units Per Short Ton of Aluminum	Per Short Ton of Aluminum		
				Toth	Shore & OTEC	Total
Clay	Short Ton	10.00	5.70	57.00		
Chlorine	Short Ton	150.00	0.076	11.40		
Oxygen	Short Ton	20.00	1.47	29.40		
Water	l.s.			1.41		
Coke (Green)	Short Ton	50.00	1.22	60.80		
Purchased Fuel (Toth)	MBTU	5.00	16.10	80.50		
Purchased Fuel Remelt	MBTU	5.00	2.5		12.50	
Maintenance (Toth)	2.5% of C.I.			25.77		
Maintenance (Reduction & Transport)	3% of C.I.				32.09	
Maintenance (Shore)	1.5% of C.I.				13.43	
Maintenance (OTEC)	2.5% of C.I.				72.97	
				266.28	130.99	397.27
Electricity	kWhr	0.06	333.0	20.00		
Labor						
Toth	MH	9.00	5.27	47.43		
Shore Base	MH	9.00	3.19		28.71	
OTEC	MH	24.75	5.45		135.00	
Plant Overhead (45% of wages)				21.34	73.67	
Tug Cost	Day				5.00	
Taxes & Insurance	2% of C.I.			18.57	99.70	
				107.34	342.08	449.42
Total						846.69

CASE E5

ESTIMATED COSTS FOR FIVE 100 MWe FLOATING OTEC CHLORIDE REDUCTION PLANTS AND
TOTH CHLORINATION PLANT ON VIRGIN ISLANDS
ΔT = 22°C ; Annual Capacity: 362,700 MT/yr
(1980 U. S. \$)

CAPITAL COSTS		\$ x 10 ⁶	Total
Cost of Toth Plant		393.86	
Cost of the Shore Support Facility		342.07	
Cost of Barge Transportation with Storage		43.92	
Cost of Chloride Reduction Plants		383.65	
Cost of OTEC Power Systems 5 Units @ 102 MWe @ \$2798.3/kw		1,167.50	2,331.00
Cost of Land		23.60	
Cost of Offices		20.00	
CAPITAL COST FOR INVESTMENT TAX CREDIT		N.A.	
Cost for Solar Energy Investment Tax Credit		N.A.	

PRODUCTION COSTS			# of Units Per Short Ton of Aluminum	\$ Per Short Ton of Aluminum		
Raw Materials	Unit	\$/Unit		Toth	Shore & OTEC	Total
Clay	Short Ton	10.00	5.70	57.00		
Chlorine	Short Ton	150.00	0.076	11.40		
Oxygen	Short Ton	20.00	1.47	29.40		
Water	l.s.			1.41		
Coke (Green)	Short Ton	50.00	1.22	60.80		
Purchased Fuel (Toth)	MBTU	5.00	16.10	80.50		
Purchased Fuel Remelt	MBTU	5.00	2.5		12.50	
Maintenance (Toth)	2.5% of C.I.			24.62		
Maintenance (Reduction & Transport)	3% of C.I.				32.09	
Maintenance (Shore)	1.5% of C.I.				12.83	
Maintenance (OTEC)	2.5% of C.I.				72.97	
				265.13	120.29	395.52
Electricity	kWhr	0.06	333.0	20.00		
<u>Labor</u>						
Toth	MH	7.25	5.27	38.21		
Shore Base	MH	7.25	3.19		23.13	
OTEC	MH	24.75	5.45		135.00	
Plant Overhead (45% of wages)				17.19	71.16	
Tug Cost	Day				5.00	
Taxes & Insurance	2% of C.I.			18.82	97.73	
				94.22	332.02	426.24
Total						821.76

CASE E COMMENTS

- (a) The capital costs of the Toth chlorination plant were scaled from Table 5.2, using the mass flow to the 0.7 power and the Chemical Engineering Cost Index. The production costs of Table 5-3 were modified to account for the fact that the AlCl_3 would be used as a product and would not be oxidized to Al_2O_3 as specified in Reference 5.10.

The capital costs were based on having five floating chloride reduction plantships, supplied with 100 MWe of OTEC power, two transfer barges which are propelled by leased tugs. It was assumed that the aluminum metal would be transferred as fine pellets, which would be remelted and cast into ingots at the shore base.

- (b) The estimated capital costs for the shorebase, transportation system and plantship reduction equipment in Case E1.1 is as follows:

	\$ x 10 ⁶	Total
AlCl_3 Storage	48.3	
Mobile Equipment	3.72	
Chlorine Storage, 80 tanks @ \$156K	12.45	
Electrolyte Regeneration	11.1	
Metal Casting	57.6	
Utilities	13.8	
Support Facilities	71.9	
Structures & Ventilation	27.6	
Pier	47.0	
		293.5

Transportation System

Barges, 2 @ \$11,000K	22.0
AlCl_3 Storage & Transport, 2 Systems	17.4
Chlorine Storage & Transport, 2 Systems	4.5
	43.9

Plantship Reduction Equipment

AlCl_3 Storage & Transfer, 5 @ \$8.7M	43.5
Rectifier, 5 @ \$8.0M	40.0
BusBars, 5 @ \$1.64M	8.2
Reduction Cell Stacks, 100 @ 0.5M	50.0
Piping Systems, 5 @ \$3.0M	15.0
Particle Casting Systems, 5 @ \$4.0M	20.0
Chlorine Recycle Systems, 5 @ \$1.0M	5.0
Chlorine Storage, 80 tanks @ 0.14M	11.2
Standby Gas Turbine Systems, 5 @ \$38.15M	190.75
	383.65

- (c) It was assumed that sale of the TiO_2 and other chemicals produced by the Toth plant would add the equivalent of 2.7¢/lbm to the sales price of the aluminum produced.

- (d) The OTEC plantship manning is as given in Table D and E. Labor for the shore base was allocated on the basis of % of capital cost as follows:

(e) Labor for Shore Support Base

Assumption: Allocate on basis of capital costs

<u>Item</u>	<u>Capital</u>	<u>MH/Ton</u>	<u>M.Hr/\$ Capital x 10⁹</u>
Toth	337.93	5.27	15.595
OTEC & Reduction	1810.78	6.02	3.314
Shorebase & Transport	337.42	3.19	9.45

- (f) The Toth chloride process plant capital costs from the previous case were scaled as mass flow to the 0.7 power. The capital cost of the shorebase was scaled from Case E1.1 as mass flow to the 0.7 power, and the capital costs of the transportation system and onboard reduction plant equipment were scaled directly with throughput.

TABLE D. MANPOWER REQUIREMENTS FOR FIVE 100 MWe OTEC
ALUMINUM CHLORIDE REDUCTION PLANTSHIPS

	Per Shift	Per Crew	Per Case
A. POWER STATION CREW			
Master	-	1	5
Mates	-	2	10
Chief Engineer	-	1	5
Chief Diver	-	1	5
Shift Foreman	1	2	10
Control Room Operator	1	2	10
Roving Operator/Diver	2	4	20
Mechanic/Pipe Fitter	2	4	20
Electronic/Instrumentation	3	6	30
Mechanic/Welder	2	4	20
Power Station Total		27	135
B. REDUCTION PLANT			
Tour Foreman	-	1	5
Safety	-	1	5
Laboratory	-	3	15
Supervision	2	4	20
Maintenance/Mechanical	5	10	50
Maintenance/Electrical/Instrumentation	5	10	50
Potroom Operation (20 Assemblies)	2	4	20
Pelletizing	1	2	10
Chlorine Recovery	1	2	10
Loading/Unloading	-	6	30
Electrolyte Reprocess	1	2	10
Reduction Plant Total		45	225
C. HOTEL STAFF			
Chief Steward	-	1	5
Doctor/2 Medical Technicians	-	3	15
Cooks/Bakers	3	6	30
Utilitymen (Stewards/Galley/Laundry)	9	18	90
Hotel Staff Total		28	140
CREW TOTAL		100	500

$$\frac{500 \text{ People} \times 84 \text{ hr/wk} \times 52 \text{ wks/yr}}{362,700 \text{ MT/yr}} = 6.02 \text{ MH/MT}$$

TABLE E. MANPOWER REQUIREMENTS FOR A 400 MWe OTEC
ALUMINUM CHLORIDE REDUCTION PLANTSHIP

	Per Shift	Per Crew	Per Case
A. <u>POWER STATION CREW</u>			
Master	-	1	2
Mates	-	2	4
Chief Engineer	-	1	2
Chief Diver	-	1	2
Shift Foreman	1	2	4
Control Room Operator	1	2	4
Roving Operator/Diver	8	16	32
Mechanic/Pipe Fitter	8	16	32
Electronic/Instrumentation	12	24	48
Mechanic/Welder	8	16	32
Power Station Total		82	162
B. <u>REDUCTION PLANT</u>			
Tour Foreman	-	1	2
Safety	-	1	2
Laboratory	-	3	6
Supervision	2	4	8
Maintenance/Mechanical	20	40	80
Maintenance/Electrical/Instrumentation	20	40	80
Potroom Operation (80 Assemblies)	3	6	12
Pelletizing	2	2	4
Chlorine Recovery	1	2	4
Loading/Unloading	-	12	24
Electrolyte Reprocess	1	2	4
Reduction Plant Total		113	226
C. <u>HOTEL STAFF</u>			
Chief Steward	-	1	2
Doctor/2 Medical Technicians	-	3	6
Cooks/Bakers	3	16	32
Utilitymen (Stewards/Galley/Laundry)	9	48	96
Hotel Staff Total		68	136
CREW TOTAL		263	524

$$\frac{524 \text{ People} \times 84 \text{ hr/wk} \times 52 \text{ wks/yr}}{580,320 \text{ MT/yr}} = 3.94 \text{ MH/MT}$$

APPENDIX B: ENERGY BRIDGE CONCEPTS

I. Use of an OTEC Product to Generate Electricity Onshore for Aluminum Plants

We have explored the feasibility of using chemical energy carriers for delivery of OTEC power to shore for reconversion to electricity for aluminum production. In this concept, OTEC plantships are sited in areas of high ΔT , such as tropical oceans, and the "energy bridge" materials^(1-33,34,35) are delivered to shore-based production plants by more or less conventional carriers. The most promising chemical-energy carriers analyzed are liquid ammonia and hydrogen.

The theoretical minimum energy required to convert bauxite to aluminum ingot shown in Figure 1-6 is 28.3×10^6 Btu/ton. The efficiency of aluminum production, based on the energy consumption values is 14.9%, where it is assumed that the electrical input is equivalent to 10,500 Btu/kWh and the heating value of natural gas is 1,000 Btu ft³.

Although the Bayer and Hall process Plants for alumina production are often located at separate sites, it is feasible to locate plants for both processes together. For example, Reynolds has both at Corpus Christi, Texas; Alcoa has both at Point Comfort, Texas, and Kaiser Aluminum has both at Gramercy, Louisiana. Therefore, an integrated plant concept is assumed.

a) Ammonia as the Reduction Energy Source

Liquid NH₃ can be manufactured on OTEC plantships and transported to shore to feed fuel cells as shown in Fig. B-1 and discussed in Ref. 1. The ammonia is made from three parts by volume hydrogen produced through electrolysis of distilled sea water and one part by volume nitrogen extracted from the air. The gases are combined under high pressure in the presence of a catalyst to form ammonia, which is liquefied on board the OTEC plantship for periodic pickup by a tanker for transportation to shore. On shore, it may be stored indefinitely at room temperature in pressure containers, and it can be transported inland by pipeline, barge, truck or rail. At the desired point of use it can be heated in the presence of catalysts to regenerate the H₂ and N₂. Dissociation begins as low as 572°F and is nearly complete at 950-1100°F. The gaseous hydrogen can serve as the fuel for fuel cells to produce electricity by reaction with oxygen to form water. The molten carbonate fuel cell operating in a cogeneration mode appears ideally suited for using the dissociated ammonia to provide both electricity and heat for aluminum production.

In the molten carbonate fuel cell (MCFC) the charge carrier is the CO₃⁻ ion, and a source of CO₂ must be available at the cathode to provide these ions. When using the MCFC to power a Hall process alumina reduction plant, the off-gases from the Hall cells provide a source of CO and CO₂ (in about equal parts) which is directly related to the current produced. However, this exhaust from the reduction cells also has traces of H₂S, and particulates including alumina and fluoride salts. Therefore, the CO/CO₂ gas has to be cleaned and compressed to the fuel-cell operating pressure which is currently about 100 psia, but could be lower. Oxygen for the fuel cell is supplied through compressed air. The compressor work for air and CO

Fig. B-1. Ammonia Energy Bridge Concept

Fig. B-2. Integration of Molten Carbonate Fuel Cell Using NH₃ with Aluminum Production Plant

and CO_2 is not included in these calculations. The fuel-cell heat rate for hydrogen is assumed as 6800 Btu/kWh. Hydrogen and carbon monoxide enter the MCFC at the anode. Hydrogen reacts with carbonate ions to produce electrons for the external circuit, and CO_2 and steam are exhausted; CO_2 and O_2 are introduced to the cathode to combine with the electrons returning from load, forming carbonate ions and thereby completing the process. The electrolyte is a lithium-potassium carbonate mixture in a ceramic support matrix.

In the cogeneration scheme shown in Fig. B-2, cracked ammonia and air are supplied to the MCFC, producing direct current which is supplied to alumina reduction cells. The waste heat at 1200°F available from the MCFC is used to produce high-pressure steam to drive a turbine to augment the electric power available, and the exhaust steam from the turbine is delivered to the Bayer process. In the energy balance calculations, the heating values of NH_3 and CO are taken as 9,668 Btu/lb and 316 Btu/ft³, respectively. The scheme matches both the thermal and electric requirements and results in an energy consumption of 112.9×10^6 Btu/ton of aluminum production. This represents an energy efficiency of 25% for aluminum production versus the nominal 14.9%. The energy utilization of fuel cells is 90.5%. We may note that NH_3 or H_2 could also be used as a fuel source for the alumina and electrode calcining steps in place of the natural gas inputs shown in Fig. B-2 without changing the efficiency of energy utilization.

To examine the economics of utilizing OTEC derived ammonia we examined the case where it is used to power a Bayer-Hall Complex on the U.S. Gulf Coast using molten carbonate fuel cells. In this case we are considering the option where the OTEC energy is converted to ammonia (NH_3) which is then delivered by pipeline or tanker to the shore based plant. At the fuel cell power plant, the ammonia is dissociated to produce hydrogen and nitrogen, which are then passed to the fuel cell.

Since we do not have firm data at the present time on the capital and operating costs for the equipment required to produce ammonia on the OTEC platform, we have made a parametric analysis where we calculate the rate of return for the Gulf Coast based Bayer-Hall production complex as a function of the cost of OTEC derived ammonia. The capital cost of the Hall plant is modified to account for the deduction of the substation and rectifiers for the potline, and the addition of the fuel cell system. The operating costs are modified to take into account the fact that purchased electricity is no longer required and there is a very large reduction in purchased fuel for the Bayer plant, the only carbonaceous fuel required is for calcining. However, NH_3 could be decomposed and the hydrogen could also be used for calcining. A breakdown of the capital costs and operating costs for this configuration are given in Appendix A as Case A1.3.

The rate of return as a function of ammonia purchase price is shown in Fig. B-3 for the three financing options, and the two investment tax credit (ITC) situations indicated by (1) and (2). Notation ITC = Project designates that the investment tax credit is limited to the project and ITC = \$3000 million designates the unconstrained investment tax credit discussed in Section 3.1. It was determined that a parent company with a \$3,000 million income

Fig. B-3. Rate of return as a function of ammonia purchase price for Bayer-Hall aluminum production complex on U. S. Gulf Coast powered with OTEC derived ammonia used in molten carbonate fuel cells, for investment tax credits (ITC) assumed limited to the project, or to a \$3000 million income tax liability.

tax liability could use all of the investment tax credits during the first profitable year of the project. In Fig. B-3 we see that for ammonia costs greater than \$100/MT, the project which involves construction of a new Bayer Plant and a new Hall Process reduction plant complex becomes unprofitable. It is assumed that the solar energy investment tax credit was used in deriving the delivered price of the OTEC derived ammonia.

This suggests that an important market for OTEC-derived ammonia may be as a molten carbonate fuel cell energy source to power existing Bayer-Hall complexes along the U.S. Gulf Coast, or sites which have an existing Bayer plant where Hall process reduction capacity could be added. These sites are shown in Fig. B-4 with their distances from potential OTEC plant sites for producing ammonia. In many cases, these plants now use natural gas as the energy source, as previously cited. With the existing plants almost fully depreciated, the potential savings made possible by substituting relatively inflation proof OTEC-derived ammonia for natural gas may present rates of return sufficiently above the threshold for investment criteria to be attractive for active consideration when both the molten carbonate fuel cell and the OTEC ammonia plant are ready for commercialization.

The ammonia-molten carbonate fuel cell system is a "safe" option. The ammonia can be stored at the site so that in event supplies are interrupted by storms or maintenance, etc., the production plants can continue to operate at 100% capacity for whatever time storage has been provided. In addition, ammonia is available in bulk quantities from commercial sources, although maybe not at the prices it would be from the OTEC plantship.

Fig. B-4. Potential U.S. OTEC/Aluminum Commercialization Sites using OTEC-Derived Ammonia in Molten Carbonate Fuel Cells

Therefore, in the event of a catastrophe at sea, aluminum production could be continued using the commercial sources, although not as profitably, until such time as the OTEC ammonia plant could be placed back in an operational status and production resumed.

An evaluation of using OTEC-derived ammonia in molten carbonate fuel cells as a retrofit to existing plants is site specific, and is outside the scope of the present project, but is suggested as a topic for future investigation because of the potential for early adoption by the aluminum industry if OTEC derived alumina (or other fuel) is available at competitive prices.

b) Hydrogen as the Reduction Energy Source

Hydrogen from the OTEC platform delivered as liquid to the shore and vaporized can also be used in molten carbonate fuel cells in a cogeneration mode to produce aluminum as shown in Figure B-4. The energy consumption is 113.3×10^6 Btu per ton of aluminum, which represents an energy efficiency of 25% for aluminum production. Energy utilization in fuel cells is 81%. Table B-1 shows the energy requirements for the baseline case as well as the ammonia and hydrogen powered energy bridge options.

An alternative hydrogen transportation system which is now in limited use in demonstration automobiles is the use of metal hydrides which may achieve hydrogen storage densities that approach the density of LH_2 ($4.4 \text{ lb H}_2/\text{ft}^3$), (41,42) a major drawback of hydride systems for massive storage and transportation of hydrogen is the high capital cost of the materials (several dollars for one pound of hydride which would contain about 1 gram of hydrogen), although new hydride systems using potentially lower cost materials are under continuing investigation. Although metal hydrides are an exciting future prospect, their present limitations preclude an accurate forecast of when an economical and thermally acceptable hydride will be available.

TABLE B-1

COMPARISON OF ENERGY CONSUMPTION
IN ALUMINUM PRODUCTION PLANTS
USING FUEL CELL OPTIONS

	Conventional Plant	Fuel Cell Integrated Plant	
	10 ⁶ Btu	NH ³ 10 ⁶ Btu	H ₂ 10 ⁶ Btu
1. Bayer Process			
a. Soda ash and lime	5.4	5.4	5.4
b. Steam	17.9	-	-
c. Electricity	1.8	-	-
2. Calcination, Natural Gas	6.3	6.3	6.3
3. Electrode production			
a. Raw petroleum, coke, etc.	19.9	19.9	19.9
b. Natural gas	2.1	2.1	2.1
4. Hall Process			
a. Fluorides	6.5	6.5	6.5
b. Electricity	130.2	-	-
c. Fuel	<u>-</u>	<u>72.7</u>	<u>73.1</u>
Total energy consumption	190.1	112.9	113.3
Theoretical energy requirement per ton of aluminum	28.3	28.3	28.3
Efficiency of aluminum production	14.9%	25%	25%

Fig. B-5 Integration of Molten Carbonate Fuel Cell Using Hydrogen with Aluminum Production Plant

As a method of reducing the transportation cost, an investigation was made of a concept called the "towed-underwater-tanker (T.U.T.)." In this concept, gas is transported in a pressure-equalized concrete/steel, dirigible-shaped container at a depth of 3000 ft (100 atmospheres) where hydrogen gas has one-sixth the volume of LH_2 . The system appears to require a small fraction of the cost of a liquefied system. Two 1000 ft tankers and one tug would be required for a single 100 MW OTEC production rate of 57 tons per day. At a distance of 4600 miles (4000 nautical miles) from the ATL 1 site to New York or New Orleans, the estimated cost of the T.U.T. system would be about one mile per million Btu's/mile ($\$4.6/10^6$ Btu/4600 mi or $\$184/\text{ton}$). Storage at New Orleans could be done in depleted natural gas wells or salt domes - the least expensive means of storage. Hydrogen could then be transported by pipelines which would require more frequent repressurizing stations than for natural gas transmission. This advanced concept could develop into an efficient system provided the future cost of electrolytically produced hydrogen will become competitive with hydrogen produced from residual oil or by coal partial oxidation methods. Two T.U.T.'s could deliver 2.34 trillion Btu/Yr.

Another energy bridge system considered was the use of either HCl or HBr in fuel-cell/electrolyzer systems. The HCl or HBr is dissociated by electrolysis on the OTEC platform. The H_2 and either Cl_2 or Br_2 are then transported to the shore-based reduction plant where they are recombined in the fuel cells generating DC electricity to run the potlines. The resulting HCl or HBr is then transported back to the OTEC platform for electrolysis again. Because of the very low polarization losses, these systems can be

Fig. B-6. OTEC Redox Cell Electricity Transmission Concept

more energy efficient than the H_2 - O_2 system. However, one must again face the problems of transporting H_2 . One variant of the H_2 - Cl_2 system is to convert the HCl which comes from the fuel cell at the shore-based plant into Cl_2 which is then recycled to the fuel cell. This is done using a modern version of the Deacon process which has been developed by Kellogg and DuPont and which is known as the KelChlor process. By this method, it is only necessary to transport hydrogen, presumably obtained by the electrolysis of water from the OTEC platform to the shore based plant, and nothing has to be hauled back.

II. Redox Battery Energy Bridge Concept

The redox battery is a rechargeable, or secondary, electric battery in which the chemical energy is stored in the electrolyte rather than on the battery plates. Thus the storage capacity of the redox battery can be very large, without adding the costs of large electrodes. The redox-flow battery considered in this study uses the ferrous/ferric redox couple and chromous/chromic redox couple as the positive and negative reactants, respectively.

The system for OTEC electricity transmission by redox battery would consist of a redox battery charging system on board the OTEC plant, sufficient tanker capacity to transport redox liquor to and from shore, and a battery discharging facility similar to the battery charging facility to accept redox liquor from the incoming tankers (Fig. B-6). The roundtrip electrical efficiency (OTEC electricity to onshore electricity) is estimated to be 75%. NASA/Lewis Research Center has developed the NASA-Redbox concept^(43,44) from the original idea (U.S. Patent No. 3,996,064) to a complete redox energy storage system at the kW level.⁽⁴⁾ These systems promise to be very inexpensive and possess many features that provide for flexible design, long life, high reliability, and minimal operation and maintenance costs. However, the transportation cost for the weak redox liquor (0.012 kWh/kg) is so high that the system is impractical for an OTEC-to-onshore-aluminum-plant energy bridge. This fact is illustrated as follows.

The number of barges required and ship capacity of a 100, 500, and 667 MW_e OTEC plant delivering the necessary quantities of chemicals for operation based on one-way transmission distance of 125, 200, and 500 miles are computed using the following assumptions. Konopka, et al,⁽³⁵⁾ made similar calculations for Fe-Ti redox couple battery assuming an energy density of 0.0135 kWhr/kg.

- o Energy density of Fe-Cr liquor is 14.5 watthour per liter of solution or 0.012 kWhr/kg
- o System sized on 100% plant availability.
- o Ship speed is 16 mph, no delay factor.
- o One barge is always at the OTEC plant and one at the onshore facility.

The following equations are utilized for calculating the number of barges and ship capacity requirements.

$$SC = \frac{2 TD}{(NB - 2)} \frac{PS 10^3 \times 2.2046}{16 \times DW \times 2000} = 0.1378 \frac{TD \times PS}{DW \times (NB - 2)}$$

$$NB = 0.1378 \frac{TD \times PS}{DW \times SC} + 2$$

Where SC = ship capacity in tons (no greater than 120,000 MT, DW = energy storage density (kWhr/kg), PS = OTEC plant size (MW_e), TD = transport distance, one-way miles, and NB = number of barges. The results are:

OTEC Plant Size MW e	Transport Distance Miles	Ship Capacity Tons	Number of Barges
100	125	71,800	4
	500	95,700	8
667	125	119,700	10
	500	119,700	34

Having established the physical dimensions of the system, we may now examine the capital costs for the 667 MW_e electric system 125 miles offshore as follows:

	$\$ \times 10^6$
Cell Stacks	160.0
Redox Chemicals	175.0
Ships, 10 @ \$ 85 x 10 ⁶ ea	850.0
	1,185.0

or \$17776/kW for transmission from the OTEC platform to shore.

For comparison, the MITRE OTEC Cost Forecast Tree estimates that the cost of 100 mile cable would be about \$284/kw. Therefore, the estimated cable cost for 667 MW_e is \$189 million, about half an order of magnitude less than the Redox energy delivery system. We therefore conclude that the Redox system is not cost effective when using 1 M solutions. The ability to use higher concentrations of salts in the liquors up to the solubility limits would make the Redox system closer to being competitive with a cable.

III. Aluminum-Air Battery for Automotive Use Onshore

The use of OTEC derived energy to produce aluminum which can be used as a fuel for an aluminum-air battery is one way that solar energy may potentially benefit the transportation sector of the economy. The aluminum-air battery is being developed by an industrial team under the leadership of the Lawrence Livermore National Laboratory. For purpose of analysis, we assumed that the recycle $\text{Al}(\text{OH})_3$ delivered to the OTEC plantship would be of adequate purity so that following a calcining step it could be input to the reduction process as Bayer grade alumina. (Thus, we can eliminate most of the capital and operating costs for the Bayer plant).

We assumed that there were three process options for using the recyclable $\text{Al}(\text{OH})_3$. The first step in each option is to calcine the $\text{Al}(\text{OH})_3$ to Al_2O_3 , which is then used as input feed to: (1) a new conventional Hall process reduction plant using purchased electricity at \$0.030/kWhr (1980 price); (2) a new conventional Hall process reduction plant on the U.S. Gulf Coast using OTEC derived electricity delivered to shore by means of a cable; and (3) and OTEC/aluminum plantship where the Bayer grade alumina is chlorinated on board using what is called the "Alcoa" chlorination process described in Section 2.4 to produce AlCl_3 which is then reduced in bipolar cells to produce aluminum metal. These options are shown in Figure B-7. The Alcoa chlorination process was assumed because data on alternative chlorination processes which do not use No. 6 fuel oil as an input feedstock was not available. Use of other sources of carbon might be more economical.

With the mid-1980 selling price of aluminum established at \$0.72/lbm, the economic model described in Sections 3.1 and 3.2 was used to calculate the rate of return which could be realized by the aluminum producer as a function of the price paid at the plant loading dock for the recyclable $\text{Al}(\text{OH})_3$. The rates of return for the three process options are shown in Fig. B-7. The details of the capital cost and operating cost estimates are presented in Tables B-2, -3, and -4.

It is seen in Figure B-8 that as the amount paid for the recyclable $\text{Al}(\text{OH})_3$ increases above a few cents per pound, the rate of return drops sharply, and for rates in excess of about 5¢/lbm, there will be no apparent return on investment if new facilities must be constructed under the conditions assumed in our baseline case.

Fig. B-7 OTEC Energy Bridge Concepts using Aluminum-Air Battery for Electric Vehicles

Fig. B-8 Variation of Rate of Return with the Recyclable $Al(OH)_3$ Price for Aluminum-Air Battery Energy Bridge Concept

TABLE B-2

ESTIMATED COSTS FOR A HALL PLANT ON U.S. GULF COAST, USING RECYCLE $\text{Al}(\text{OH})_3$
(1980 U.S. \$)Location: U.S. GULF COAST
ANNUAL CAPACITY: 399,695 ST/yr

CAPITAL COSTS		\$ x 10 ⁶	Total	
Cost of Calcine Plant		30.92		
Cost of Hall Plant		937.28		
TOTAL CAPITAL COST			968.20	
Cost of Land		23.60		
Cost of Offices		<u>5.70</u>		
CAPITAL COST FOR INVESTMENT TAX CREDIT			938.90	

PRODUCTION COSTS			# of Units Per Short Ton of Aluminum	\$ Per Short Ton of Aluminum	
	Units	\$/Unit		Hall	Total
<u>Raw Materials and Other</u>					
Cryolite	Short Ton	493.90	0.035	17.29	
Aluminum Fluoride	Short Ton	514.50	0.02	10.29	
Maintenance Materials	2.5% of C.I.			<u>64.60</u>	
					92.18
Purchased Fuel	10 ⁶ BTU	4.00	9.65	38.60	
Purchased Fuel	10 ⁶ BTU	4.00	6.60	26.40	
Calcined Coke	Short Ton	120.00	0.52	62.40	
Pitch	Short Ton	103.00	0.15	<u>15.45</u>	
					142.85
Labor Calcine	MH	14.50	0.5	7.25	
Labor, Hall	MH	14.50	8.00	116.00	
Plant Overhead (45% of Wages)				69.60	
Local Taxes & Insurance	2% of C.I.			<u>51.68</u>	
					244.53
Subtotal					479.56
<u>Energy</u>					
Electric Power	kWhr	0.03	14,168.00		425.04
Total					<u>904.60</u>

TABLE B-3

ESTIMATED COSTS FOR A HALL PLANT ON U.S. GULF COAST
USING RECYCLE $\text{Al}(\text{OH})_3$ POWERED BY OTEC THROUGH CABLE
(1980 U.S. \$)

Location: U.S. GULF COAST -
 ΔT - 20°C; Cable length, 100 miles
 ANNUAL CAPACITY: 399,695 ST/yr
 771,412 ST/yr Al_2O_3

CAPITAL COSTS		\$ x 10 ⁶	Total		
<hr/>					
OTEC Plant Costs					
636.7 MW x 2655 x 10 ³ \$/MW		1,690.04			
<hr/>					
Total Capital Cost for Solar Energy					
Tax Credit					1,690.04
<hr/>					
Capital Cost of Calcine Plant					
7.7 x 10 ⁵ x 40 \$/ton		30.86			
<hr/>					
Capital Cost of Hall Plant		937.28			
<hr/>					
TOTAL CAPITAL COST					2,658.18
<hr/>					
Non Investment Tax Credit Costs		29.30			
<hr/>					
CAPITAL COST FOR INVESTMENT TAX CREDIT					2,628.88
<hr/>					
			# of Units Per Short Ton of Aluminum	\$ Per Short Ton of Aluminum	
PRODUCTION COSTS	Units	\$/Unit		Hall + OTEC	Total
<hr/>					
<u>Raw Materials and Other</u>					
Cryolite	Short Ton	493.90	0.035	17.29	
Aluminum Fluoride	Short Ton	514.50	0.02	10.29	
Maintenance Material (Hall)2.5% of C.I.				64.60	
Maintenance Material (OTEC)2.5% of C.I.				116.62	
					208.70
<hr/>					
Purchased Fuel/ Calcine	10 ⁶ BTU	4.00	9.65	38.60	
Purchased Fuel/ Electrodes	10 ⁶ BTU	4.00	6.60	26.40	
Calcined Coke	Short Ton	120.00	0.52	62.40	
Pitch	Short Ton	103.00	0.15	15.45	
					142.85
<hr/>					
Labor, Calcine	MH	14.50	0.5	7.25	
Labor, Hall	MH	14.50	8.00	116.00	
Labor, OTEC	MH	22.50	3.07	69.08	
Plant Overhead (45% of wages)				86.55	
Local Taxes & Insurance 2% of C.I.				144.90	
					423.78
<hr/>					
					775.33
<hr/>					
<u>Energy</u>					
Electric Power	kWhr	0.03	1,416.8		42.50
(10% of Total Requirement)					
<hr/>					
Total					817.83
<hr/>					

TABLE B-4

ESTIMATED COST BREAKDOWN OF A CHLORINATION AND REDUCTION
PLANT ONBOARD THE OTEC PLANTSHIP, USING RECYCLE Al(OH)_3
(1980 U.S. \$)

Product: Aluminum
Location: U.S. Off Virgin Islands
ANNUAL CAPACITY: 160,000 ST/yr

CAPITAL COSTS	\$ x 10 ⁶	Total
OTEC 200 MW _e @ \$2,172.00/kW	434.4	
Additional Cost, for less than 400 MW _e	174.6	
Chlorination & Reduction Equipment	406.8	
Shore Base Facilities:		
Support Facilities	10.0	
Pier	25.0	
Metal Casting	23.1	
Storage	10.0	
Mobile Equipment	1.5	
Calcining Equipment	12.4	
Structures	10.0	
Utilities	9.0	
Total Shore Base Facilities	101.0	
ESTIMATED TOTAL CAPITAL COST		1,116.80

PRODUCTION COSTS	Units	\$/Unit	# of Units Per Short Ton of Aluminum	\$ Per Short Ton of Aluminum	
			Shore & OTEC	Total	
<u>Raw Materials and Other</u>					
Al(OH) ₃	Short Ton	Variable	2.89	Variable	
Chlorine	Short Ton	150.00	0.19	28.50	
Oxygen	Short Ton	20.00	0.02	0.40	
Water	l.s.			1.41	
Purchased Fuel, Calcine	MBTU	5.00	9.65	48.25	
Purchased Fuel (Chlor)	MBTU	5.00	24.85	124.25	
Purchased Fuel Remelt	MBTU	5.00	2.5	12.50	
Maintenance					
(Chlor & Red.)	3% of C.I.			76.28	
Maintenance (Shore)	1.5% of C.I.			9.50	
Maintenance (OTEC)	2.5% of C.I.			95.16	
					396.25
Labor, Shore Base	MH	7.25	4.00	29.00	
Labor, OTEC	MH	24.75	7.94	196.52	
Plant Overhead					
(45% of wages)				101.48	
Tug Cost	Day	5.00	2.0	10.00	
Taxes & Insurance	2% of C.I.			139.61	
					476.61
Total					872.86