MASTER

ENERGY CONSERVATION IN THE
PRIMARY ALUMINUM AND
CHLOR-ALKALI INDUSTRIES

Contract No. DE-AC02-80CH10026

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Hittman Associates, Inc.

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Compiled for the Department of Energy

By

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October 1980

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I. INTRODUCTION

The primary aluminum and chlor-alkali industries together use nearly 13 percent of the electrical energy consumed by U.S. industry.* As part of its mission to promote energy conservation in basic U.S. industries, the DOE is surveying the present technological status of the major electrochemical industries and is evaluating promising technological innovations which may lead to reduced energy requirements. The objective of this study is to provide technical and economic analyses in support of a government program of research and development in advanced electrolytic technology. This program is intended to supplement the development efforts directed toward energy savings by private industry. Sections II and III of this report cover aluminum and chlorine production processes only, since these two industries represent over 90 percent of the electrical energy requirements of all electrolytic industries in the United States. Section IV examines barriers to accelerated research and development by the electrolytic industries, and makes suggestions for government actions to overcome these barriers.

*1978 Electrical energy use in primary aluminum:	79.8 x 10 ⁹ kWh
1978 Electrical energy use in chlor-alkali:	31.0 x 10 ⁹ kWh
1978 Total industrial electrical energy use (utility sales to industry + self-generated)	854.4 x 10 ⁹ kWh

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II. PRIMARY ALUMINUM

A. Production Capacity

Worldwide primary aluminum production capacity at the end of 1979 was 19,147,000 tons per year. The six major producers are (1):

• United States	5,281,600 tons/year
• USSR	2,760,000 tons/year
• Japan	1,787,000 tons/year
• Canada	1,254,000 tons/year
• West Germany	898,000 tons/year
• Norway	777,000 tons/year

The United States' primary aluminum production capacity is 27.6 percent of worldwide capacity. Tables II-1 and II-2 contain information on domestic primary aluminum production capacity. Table II-1 lists the plant location, capacity, and startup date, by company, for the 32 aluminum smelting plants in the United States at the end of 1979. The type of anode used and electric power source are also shown for each plant. The Bonneville Power Administration supplied approximately 30 percent of the electric power used in aluminum smelting in 1979. At the end of 1979, 162,500 tons/year of U.S. aluminum smelting capacity in the Pacific Northwest was shut down because of electric power cutbacks. Table II-2 lists the aluminum smelting plants which are planned or under construction in the United States (2).

B. Electrical Energy Requirements For The Hall-Héroult Aluminum Reduction Process

The electrolytic or Hall-Héroult process for producing aluminum requires aluminum oxide, a dry, fine white powder (alumina) extracted from bauxite by the Bayer process, and molten cryolite, which serves as the electrolyte. Direct current passes through the cryolite bath in a cell and electrolytically decomposes the alumina which is periodically added to the carbon-lined cell (see Figure II-1). The

TABLE II-1. PRIMARY ALUMINUM PRODUCTION CAPACITY - U.S.

(December 31, 1979)

Company	Plant Location	Year of Start-up	Capacity (Short Tons/yr)	Anode Type	Electrical Power Source
Alcoa	Massena, New York	1903	215,000	Prebaked	Hydro (plan to use nuclear)
	Baden, New York	1916	124,000	Prebaked	Hydro
	Alcoa, Tennessee	1914	237,000	84% Prebaked 16% Soderberg	20% Hydro 80% Thermal
	Point Comfort, Texas (planned to be closed down)	1949	185,000	Soderberg	Thermal
	Rockdale, Texas	1952	310,000	Prebaked	Thermal
	Palestine, Texas	May 1976	30,000	Alcoa Smelting Process	50% Hydro 50% Thermal
	Vancouver, Washington	1940	115,000	Prebaked	Hydro*
	Wenatchee, Washington	1952	205,000	Prebaked	Hydro*
	Evansville, Indiana	1960	290,000	Prebaked	Thermal
Anaconda Aluminum Co.	Sebree, Kentucky	1974	120,000	Prebaked	Hydro
	Columbia Falls, Montana	1955	180,000	Soderberg	Hydro*
Consolidated Aluminum Corp.	Lake Charles, Louisiana	1974	36,000	Prebaked	Thermal
	New Johnsonville, Tennessee	1963	144,000	Prebaked	20% Hydro 80% Thermal
Noranda Aluminum, Inc.	New Madrid, Missouri	1971	140,000	Prebaked	Thermal
Martin Marietta Aluminum, Inc.	The Dalles, Oregon	1958	90,000	Soderberg	Hydro*
	Goldendale, Washington	1972	120,000	Soderberg	Hydro*
Eastalco	Frederick, Maryland	1970	176,000	Prebaked	Thermal
Intalco	Bellingham, Washington	1966	260,000	Prebaked	Hydro*
Kaiser Aluminum & Chemical	Chalmette, Louisiana	1951	260,000	Soderberg	Thermal
	Mead, Washington	1942	220,000	Prebaked	Hydro*
	Tacoma, Washington	1942	80,000	Soderberg	Hydro*
	Ravenswood, West Virginia	1957	163,000	Prebaked	Thermal
Ormet Corp.	Hannibal, Ohio	1958	260,000	Prebaked	Thermal
Revere Copper & Brass, Inc.	Scottsboro, Alabama	1971	113,000	Prebaked	Thermal (Nuclear)
National-Southwire Aluminum Co.	Hawesville, Kentucky	1969	180,000	Prebaked	Thermal

TABLE II-1. (CONTINUED)

Company	Plant Location	Year of Start-up	Capacity Short Tons/yr	Anode Type	Electrical Power Source
Reynolds Metals Co.	Sheffield, Alabama	1940	201,000	Soderberg	20% Hydro; 80% Thermal
	Arkadelphia, Arkansas	1954	68,000	75% Soderberg 25% Prebaked	68% Thermal 32% Hydro
	Jones Mills, Arkansas	1942	124,000	Prebaked	Thermal
	Massena, New York	1953	126,000	Soderberg	Hydro
	Troutdale, Oregon	1942	130,000	Prebaked	Hydro*
	Corpus Christi, Texas	1952	113,000	Soderberg	Thermal
	Longview, Washington	1941	<u>209,000</u>	Soderberg	Hydro*
TOTAL			5,281,600 Short Tons		

*Power purchased from Bonneville Power Administration

Source U.S. Bureau of Mines. Primary Aluminum Plants, prepared by Division of Nonferrous Metals.

TABLE II-2. PLANNED EXPANSION OF U.S. PRIMARY
ALUMINUM PRODUCTION CAPACITY

Company	Plant Location	Capacity Tons/yr	Year
Alumax	Mount Holy, South Carolina	197,000 (new plant)	Mid 1981
Martin-Marietta	Goldendale, Washington	65,000 (addition to existing smelting plant)	1982
Alcoa	Most of existing Alcoa smelters	25,000	1981
		25,000	1982
		50,000	1983
		100,000	1985
Alumax Pacific Corp.	Umatillo, Oregon	187,000 (new plant)	1980
Eastalo	Frederick, Maryland	90,000 (existing plant)	1980
Anaconda	Sebree, Kentucky	60,000 (existing plant)	1980

Total Planned Expansion (1980-1985) 799,000 Tons/Year

Source: Chemical Week, January 30, 1980.

Figure II-1. Cross-Section of Aluminum Reduction Cell

electrolysis yields carbon dioxide and molten metallic aluminum which collects at the bottom of the cell. In a modern plant, long rows or potlines of 50 to 150 smelting cells are connected electrically. Because electrical power is a major cost of aluminum production, most plants are located close to the source of relatively inexpensive electric power.

The following formula represents the electrical energy requirement for aluminum reduction by the conventional/Hall-Héroult process:

$$\text{kWh/lb of Al} = \frac{135 \times \text{Cell Voltage}}{\text{Current Efficiency (\%)}}$$

Current efficiency in the most modern aluminum potlines is approximately 90 percent, with a probable upper limit of 95 percent. It is affected by the following factors:

- (1) Sidewall design, anode and cathode electrical buswork configuration
- (2) Carbon anode quality
- (3) Anode-cathode separation
- (4) Anode effects.

The cell voltage is the sum of three components: theoretical decomposition potential, cell operating overvoltage, and ohmic voltages through cell components. The theoretical decomposition voltage (1.17 volts) and the cell operating overvoltage (0.5 to 0.8 volt) are relatively constant and inherent to the process. Therefore, any significant reduction in cell voltage is accomplished by reducing ohmic losses (about 3.0 volts for typical cell). The ohmic loss for each cell component is the product of electrical resistivity, current path length, and current density through the given component. For conventional cell designs, the anode and cathode materials and current path lengths are fixed, so the only practical way to reduce ohmic losses has been to decrease current density. Unfortunately, as current density is lowered, less aluminum is produced per unit of cell and potline building size, which means higher capital cost per ton of capacity.

The average electrical energy requirement for primary aluminum plants in the United States is about 8 kWh per pound of aluminum produced (see Table II-3). The most modern American plants use from 6.15 to 6.50 kWh per pound. Older plants tend to have higher electrical energy requirements. For example, Kaiser Aluminum reports that its plants built in the 1940s use from 8 to 10 kWh per pound of aluminum. Plants

TABLE II-3. ENERGY USE AND CARBON CONSUMPTION
U.S. PRIMARY ALUMINUM PRODUCTION IN 1978

<u>Anode Preparation</u>	<u>All Values/lb of Molten Aluminum Metal</u>	
Natural gas and fuel oil (used for prebaking furnaces)	2,048 Btu	
(91% natural gas/9% petroleum products)		
Petroleum coke	0.42	lb
Pitch coke	0.10	lb
Coal	0.02	lb
<u>Reduction Potlines</u>		
Elec - hydro	42%	
Elec - thermal, purchased	43%	8.10 kWh
Elec - thermal, self-generated	15%	

Sources: Compiled from data obtained from The Aluminum Association, Aluminum Statistical Review, 1978,

and

The Aluminum Association, Energy Conservation and the Aluminum Industry. 1979

built in the 1950s use from 7.5 to 8 kWh/lb. Those built in the 1960s use 6.8 to 7.5, and those built in the 1970s use 6.1 to 7.2 kWh/lb.

The practical limit to reducing electrical energy requirements in present-technology Hall-Héroult cells has nearly been reached in a few of the most modern and carefully operated plants (3). This limit is between 5.6 and 5.9 kWh/lb. These plants operate at an anode current density of 4.6 amps/in² (0.72 A/cm²) and have a cell voltage of 3.87 volts. Table II-4 compares five countries' electrical energy usage per pound of aluminum smelted. The significant difference between electrical energy requirements in France and the United States can be attributed to two factors:

- (1) The cost of industrial electricity has been considerably higher in France than in the United States.
- (2) French aluminum smelting plants are, on the average, more modern than American plants.

C. Projection of Availability and Price of Raw Materials

The two primary raw materials consumed in the production of aluminum are bauxite ore and petroleum coke (used in production of the consumable anodes). The availability and future price of petroleum coke depends on the world market for petroleum. At its current price of approximately \$200 per ton, the petroleum coke required per pound of primary aluminum (0.42 lb) adds \$.042 to the production cost.

Figure II-2 shows the materials flow of bauxite ore and alumina (Al₂O₃ is extracted from bauxite and reduced to form aluminum metal) for the United States in 1979. In 1979, U.S. mine production of bauxite provided only 436,000 short tons of aluminum metal (8.6 percent of U.S. primary aluminum production). Since U.S. reserves of bauxite are approximately 45 million short tons, the United States will be dependent on imports of the ore for over 90 percent of aluminum production in the foreseeable future. It is likely that in the future a larger percentage of the raw material for primary aluminum production will be imported as alumina rather than bauxite. This is because the developing countries with large bauxite reserves are striving to develop their own alumina production capacities.

World bauxite reserves, estimated to be over 25 billion metric tons, are adequate to meet demands through the year

TABLE II-4. ELECTRICAL ENERGY REQUIREMENTS
FOR PRIMARY ALUMINUM PRODUCTION

U.S.	8.1 kWh/lb aluminum (average)
France	6.9 kWh/lb aluminum (average)
Germany	7.3 kWh/lb aluminum (average)
United Kingdom	8.0 kWh/lb aluminum (average)
U.S.S.R.	6.7 kWh (most efficient plant) 7.3 kWh (typical Soderberg anode plant)

Sources: Lugagne, P. "Energy Comparisons in Primary Aluminum,"
Massachusetts Institute of Technology, 1977.

The Aluminum Association.

Kaluzhskiy, N.A. "Recent Technological Developments
in Soviet Aluminum Technology," Tsvetnye Metally,
November 1977.

Source: U.S. Industrial Outlook 1980, U.S. Department of Commerce

Figure II-2. Primary Aluminum Raw Materials Flow - 1979
(All values in million short tons)

2000. The geographical distribution of bauxite is illustrated in Table II-5. World bauxite production in 1977 is shown in Table II-6. World cumulative production of primary aluminum between 1980 and 2000 is projected at 550 million short tons (assuming an average annual growth of five percent). At 4.36 pounds of bauxite required per pound of aluminum, the cumulative worldwide consumption of bauxite between 1980 and 2000 will be approximately 2.4 billion tons. Known economically recoverable reserves are more than ten times this cumulative demand.

The current average cost of bauxite used in producing aluminum in the United States is \$30 per short ton. This includes all shipping and freight charges. Taxes levied by the exporting countries make up the major portion of this cost, since the 1.87 million tons of bauxite mined in the United States in 1978 were valued at \$12.30 per ton. Chase Econometrics has predicted that by 1985 the average cost of bauxite will be over \$51 per ton.

The International Bauxite Association (IBA), a cartel composed of 11 major bauxite-exporting nations, is attempting to establish a uniform price for bauxite based on a fixed percentage of the list price of aluminum ingot. In 1978, the IBA agreed to set the price for bauxite at two percent of the average list price for aluminum ingot. In 1979, the IBA bauxite price was approximately \$26/short ton. To date, Australia, although a member of IBA, has not gone along with this effort. However, between 1970 and 1975 the major bauxite-producing countries raised the export price by a factor of 4 through taxes and levies.

The current average price of alumina used in aluminum production is \$140 per ton. The cost of alumina constitutes approximately 20 percent of the price of aluminum ingot. Over 60 percent of this is currently produced in alumina plants in the United States and 76 percent of the imported portion comes from Australia. If the IBA is successful in its attempt to set the price of alumina at a fixed percentage (16 to 19 percent) of the list price of aluminum ingot, and if Australia were to agree, the price of alumina in 1980 would rise to \$250 per short ton. However, the price paid by U.S. aluminum producers depends primarily on relations with Australia. The Japanese conglomerate, Sumitomo, is selling alumina to the USSR for \$182 per short ton.

TABLE II-5. WORLD BAUXITE RESERVES

		Million Metric Tons
NORTH AMERICA:	United States	40
	Jamaica	2,030
	Other	180
		2,250
SOUTH AMERICA:	Brazil	2,540
	Guyana	1,020
	Surinam	500
	Other	50
		4,110
EUROPE:	Greece	760
	Hungary	200
	USSR*	150
	Yugoslavia	410
	Other	90
		1,610
AFRICA:	Cameroon	1,020
	Ghana	580
	Guinea	8,330**
	Sierra Leone	130
	Other	100
		10,160
ASIA:	China, People's Republic of	150
	India	1,420
	Indonesia	710
	Other	50
		2,330
OCEANIA:	Australia	4,570
	Other	50
		4,620
	WORLD TOTAL	25,080

Source: Bureau of Mines, United States Department of the Interior, Aluminum, May 1978 (MCP-14).

* Includes USSR in Asia.

**It is not clear whether the estimate of 8,330 million tons reflects economic resources only or includes subeconomic resources as well. In an International Bauxite Association (IBA) paper titled "Bauxites of the World and their Exploitation," September 1978, Guinea's measured resources were 3,572 million tons.

TABLE II-6. MAJOR BAUXITE-PRODUCING COUNTRIES: 1977

	THOUSAND METRIC TONS	%
<u>Europe</u>	7,131	8.4
France	2,059	2.4
Greece	2,984	3.5
Yugoslavia	2,044	2.4
<u>Africa</u>	11,863	14.0
Guinea	10,841	12.8
<u>Asia</u>	3,993	4.7
India	1,508	1.8
Indonesia	1,301	1.5
<u>America</u>	24,095	28.5
Guyana	3,344	4.0
Jamaica	11,433	13.5
Surinam	4,856	5.7
<u>Australia</u>	26,074	30.8
<u>Other</u>	11,449	13.5
Hungary	2,949	3.5
USSR	6,700	7.9
<u>World Total</u>	84,605	100

Source: World Bureau of Metal Statistics, World Metal Statistics, January 1979.

D. Recent Process Improvements

1. U.S. Companies

The following types of improvements have recently been adopted by primary aluminum producers in the United States to reduce electrical energy requirements.

- (a) Replacement of mercury arc rectifiers (94 percent efficient) with silicon rectifiers (97 percent AC-DC conversion efficiency) (4). Over 75 percent of the aluminum smelting plants now use silicon rectifiers.
- (b) Lowering of current density, thereby reducing swirling of the molten bath to minimize reoxidation of molten aluminum (Alcoa process improvements) (5). Lowest practical current density is 4.5A/in² (6).
- (c) Use of prebaked anode of increased area. The advantages of prebaked over Soderberg anodes are:
 - (1) Prebaked anodes allow more flexible process regulation
 - (2) Prebaked anodes have a lower anode voltage drop (about 0.24 volts) than Soderberg anodes (about 0.60 volts)
 - (3) While approximately ten million Btu of thermal energy is required to fabricate the prebaked anode used to make a ton of aluminum, prebaked anode plants have approximately 7 percent lower electrical energy requirements than Soderberg plants. This is due to the lower voltage drop of the prebaked anode.
 - (4) Some producers are computerizing the anode prebaking operation to improve the anode quality and thereby improve current efficiency in the potline
 - (5) Prebaked anodes emit fewer tar fumes than Soderberg anodes.
- (d) Computer process control of the potline operation using heat flux sensors to minimize occurrence of "anode effects" (i.e., evolution of fluorine gas around the anode when the alumina content of the molten bath drops to one percent).

The anode effect is accompanied by a very large voltage drop and a decline in current efficiency. Computer process control permits automated feeding of alumina and closer anode-cathode separation, thus reducing voltage drop.

- (e) Use of graphite electrode lining to reduce voltage drop.
- (f) Improved hooding to minimize heat loss. Increasing the pot size (reducing ratio of surface to volume and thereby reducing heat loss) has accounted for 95 percent of the reduction in electrical energy use in aluminum smelting since the 1950s (4). The largest reduction cells today are 230,000 amps (approximately 3,800 lbs of molten aluminum per day per cell).
- (g) Redesigning anode and cathode bus-work to improve magnetic field configuration, thereby improving current efficiency.

Alumax is planning to use process improvements licensed from Alcoa in its Charleston, South Carolina, plant.

Kaiser is retrofitting its Baton Rouge, Louisiana, plant. By 1982, average electrical energy use per pound of aluminum produced is expected to be 20 percent lower than the present average.

2. Foreign Companies

a. Sumitomo Aluminum Company (Japan). The Sumitomo Aluminum Company has patented improvements in both prebaked and Soderberg anode cells and licenses these improvements to other companies. The Sumitomo improvements include a graphite electrode lining, computer controls, and closer anode-cathode separation. Prebaked plants in Indonesia and Australia have installed these improvements and claim electrical energy consumption of 6.14 kWh (DC) per lb of aluminum (6). Sumitomo recommends prebaked anodes for new plants with a capacity of over 150,000 metric tons/yr. Martin Marietta is using Sumitomo technology in its Goldendale, Washington, plant expansion (expected to use 6.5 kWh/lb, compared to 8.15 kWh/lb in the existing plant). Sumitomo has licensed its Soderberg anode process to Norway's Norsk Hydro and Anaconda. The Soderberg process improvements are applicable for older plants. Electrical energy use of 6.4 kWh/lb is claimed. Sumitomo claims a six-year life for its cathodes (double the conventional life expectancy) (8).

b. Péchiney-Ugine Kuhlmann (France). Péchiney-Ugine Kulmann has licensed a microprocessor-controlled continuous alumina feed system for use in a new Australian smelter plant. British Aluminum Corporation, Ltd., will also use the Pechiney technology in renovating its Fort William, Scotland, plant. Péchiney's Auzat smelting plant, one of the world's most efficient, has an average electricity use per lb of aluminum of 5.9 kWh (compared to an average of 8.1 kWh/lb for American plants in 1978). The Péchiney plant has the following operating parameters (3):

- (1) Voltage per cell: 3.87V
- (2) Current efficiency: 89.5%
- (3) Anode current density: 0.72 A/cm^2
- (4) Potline current: 90,850 A.

c. USSR Technology. In the USSR, 80 percent of the aluminum smelters are equipped with automatic control systems. Older plants use vertical stud Soderberg anodes. Average electrical energy use in these plants is 7.3 kWh/lb. Plants built since 1974 have prebaked anodes and use an average of 6.7 kWh/lb. The largest potlines in the USSR are 260,000 amps. The Dneprovsk aluminum plant is the only plant in the world that produces aluminum-silicon alloy by direct reduction of aluminum sulfate (9).

E. Research and Development Efforts

1. U.S. Companies

The following areas of research are regarded by some U.S. aluminum producers as having a high near-term potential for reducing electrical energy requirements in aluminum smelting:

- Research in modified pot chemistry (i.e., additions to the molten cryolite bath)
- Research in the magnetic fields of anode and cathode bus-work to improve current efficiency
- Development of improved electrical rectifiers
- Research in cathode geometry.

These research areas are under investigation by the aluminum companies.

a. Titanium Diboride (TiB_2) Cathode Lining. Alcoa, Kaiser, and Reynolds are studying and testing TiB_2 tiles for lining the cathodes. Since this refractory material is wettable by molten aluminum, the reduction cell could be redesigned so that only a thin film of molten aluminum would serve as the cathode. (The sides of the cell floor would be slightly sloped toward a central trough which would collect most of the molten aluminum.) With a thin-film fixed cathode, the anode-cathode separation could be reduced to 0.5 to 1.0 inch, thereby reducing the voltage drop through the electrolyte from approximately two volts for conventional cells to less than one volt. In conventional cells, the anode-cathode separation is maintained at 1.5 to 2.0 inches in order to prevent shorting since the molten pad of aluminum, which serves as the cathode, surges continuously under magnetohydrodynamic forces. The electrical energy requirement for aluminum smelting could be reduced by approximately 20 percent through the use of a TiB_2 cathode lining. An important advantage is that TiB_2 cathode linings could be installed in many existing aluminum smelting plants.

While the Alcoa and Reynolds studies are entirely company-sponsored, Kaiser Aluminum and Chemical Corporation is testing TiB_2 cathodes in a pilot-scale cell under DOE funding.* In 1977 Kaiser reported an average electrolyte voltage drop in its pilot-scale aluminum reduction cell of 1.28 volts, compared to 1.9 volts before installation of the TiB_2 tiles (10). The consequent reduction in electrical energy use was 14 percent. However, the test cell was prematurely shut down due to breakage and loosening of the TiB_2 tiles that lined the cathode. The damage was attributed to probing and demucking operations. The chemical stability of the TiB_2 tiles indicated a potential service life of approximately 2,000 days. Kaiser is planning to complete a 200-day test run of TiB_2 cathode lining on a full-sized reduction cell by the end of 1980 (6). The primary problem with the TiB_2 cathode lining is the brittle nature of the material and its inability to withstand physical and thermal shocks.

b. Modifications of the Molten Bath. Kaiser is testing additions of LiF and MgF to the cryolite bath to lower the melting point of the molten salt electrolyte, thereby reducing

*M. McNeil, DOE Program Manager for this demonstration program, indicated that he believes no further basic research is needed on the TiB_2 cathode. The most recent progress report has not been released yet by his office because of patent considerations.

energy requirements. Another modification being investigated is lowering the ratio of sodium fluoride to aluminum fluoride. This may lead to a two to four percent improvement in cell energy efficiency.

c. Permanent Anodes. Alcoa is negotiating with DOE for a contract to develop permanent, inert anodes.* A permanent anode coupled with a stable cathode might permit the construction of a bipolar electrode reduction cell, which would have significantly less voltage drop and greater energy efficiency. The probability of success over the next 15 years is estimated to be 50 percent. However, the use of bipolar electrodes would not be applicable to existing pot-lines.

d. Direct Carbothermic Reduction. Alcoa has a DOE contract to test a process for thermally reducing aluminum-bearing ores to produce aluminum-silicon alloys. Such alloys (86 percent Al, 13 percent Si) are used for aluminum die casting. The demand for aluminum die casting in 1978 was 1,274 million pounds (approximately nine percent of U.S. aluminum demand). Alcoa foresees a growing potential for the use of Al-Si alloys in automobile manufacturing. A small pilot-scale "aluminum blast furnace" is in operation which is charged with coke, bauxite, and domestic aluminum-bearing clay. According to Alcoa, direct carbothermic reduction has more potential than any other candidate system for reducing the energy required to smelt aluminum. Alcoa estimated in January 1980 that it will take at least six years to develop and build a pre-commercial scale demonstration reactor. Direct reduction probably will not be ready for commercial-scale demonstration until the 1990s.** Theodore Beck, of Electrochemical Technology Corporation, estimated that the R&D effort required for direct reductions will cost \$15 million.

e. Alcoa Smelting Process. This process, which is based on the electrolytic decomposition of aluminum-trichloride, has been under development by Alcoa since 1973 and is the only alternative to the basic Hall-Hérault aluminum

*Alcoa claims that an inert anode, by enabling a closer anode-cathode spacing, can reduce electrical energy requirements to approximately 4.2 kWh per pound.

**"DR Aluminum: The Next Step Beyond Alcoa's Chloride Smelting." Engineering and Mining Journal, January 1980, p. 11.

reduction process to be tested on a large scale. Alcoa started up a 15,000 ton-per-year plant in Anderson County, Texas, in May 1976 and recently expanded it to 30,000 tons per year. The next phase of the process, which involves re-design, construction, and testing of a new segment of the chemical plant, will be completed in 1984. The process is being developed entirely with Alcoa corporate funding, and process details are available only through the patents. Alcoa plans to license the process to other companies when it has been fully developed and tested.

The Alcoa Smelting Process consists of two basic stages:

- (1) Chlorination of relatively pure alumina, using carbon to provide the reducing conditions. A two-stage fluid-bed system fired with No. 6 fuel is used. The oil is used to coat the alumina particles. Approximately 180 gallons of No. 6 oil is required per ton of aluminum produced (11). Coal-derived liquid fuel may be able to be substituted for the fuel oil if it is sufficiently low in viscosity and adheres to the alumina. The aluminum chloride is separated from the other constituents by selective condensation. The theoretical energy required for this step is 1,700 Btu/lb (100 percent thermal efficiency). A thermal efficiency of 50 percent is probable.
- (2) Electrolytic reduction of the aluminum chloride in a molten electrolyte consisting of LiCl, NaCl, and KCl. The reduction cell is said to consist of several bipolar graphite electrodes stacked horizontally. Alcoa claims that the electrical energy use is 4.5 kWh/lb of aluminum metal.

The primary advantages of the Alcoa Smelting Process over the Hall-Héroult process are (5):

- (1) Lower electrical energy consumption (4.5 kWh/lb compared to 6 kWh/lb for the best Hall-Héroult cells). This is due to the greater conductivity of the chloride electrolyte and smaller interelectrode spacing. The Alcoa Smelting Process also has lower thermal energy requirements than Hall-Héroult (3,500 vs. 5,500 Btu per lb).

- (2) Use of permanent graphite electrodes rather than consumable carbon electrodes.
- (3) From 1-1/2 to 4 times the aluminum can be produced in a plant with the same floor area as a conventional Hall-cell smelter. This is because a vertical plant layout is possible with horizontally stacked electrodes.
- (4) The Alcoa Smelting Process is a completely closed system; thus, gaseous emissions are more easily controlled than in a conventional Hall-cell potline.
- (5) There is a greater tolerance of power supply interruptions.
- (6) The electrolytic reduction takes place at 1,290°F; in the Hall process, a temperature of 1,800°F is required.

The primary technical difficulties experienced by Alcoa are probably associated with handling the extremely corrosive aluminum chloride, maintaining the purity of the AlCl_3 content in the electrolyte, and maintaining a water-free and air-free environment in the reduction cell.

Table II-7 compares the energy and carbon requirements of alternative domestic aluminum reduction processes.

h. Sulfide Processes. Basic research is underway at the Argonne National Laboratory (ANL) to investigate several possible methods of producing aluminum via a sulfide intermediate. The principal advantage of this approach is the low theoretical decomposition voltage, which is 0.98 volts (compared to 1.87 volts for the Hall-Héroult process). The processes would involve the reaction of either Bayer alumina (Al_2O_3) or bauxite with coke and sulfur to form Al_2S_3 . These intermediate products would then be electrolytically reduced to aluminum and the sulfur would be recovered. It is assumed that the electrolytic process would use a cell similar to the AlCl_3 electrolytic cell being demonstrated by Alcoa. Estimated electrical energy requirements for Al_2S_3 reduction (approximately 3.8 kWh/lb) are 15 percent less than for AlCl_3 reduction. Carbon requirements, however, are higher than for the Hall-Héroult process. They are estimated at 0.42 to 1.0 lb per pound of aluminum produced. Present efforts at ANL are being directed toward verification of the thermodynamics and electrochemistry of the various sulfide processes.

TABLE II-7. ENERGY AND CARBON REQUIREMENTS
OF ALUMINUM REDUCTION PROCESSES

(All values are per pound of aluminum metal produced.)

	Conventional Hall-Héroult Process (U.S. Average)	Modern Hall-Héroult Cell with TiB_2 Anodes ²	AlCl_3 Electrolysis (Alcoa Smelting Process)	Carbothermic Reduction to form an Al-Si Alloy
Electrical Energy (kWh per pound of Aluminum)	8.0	5.8	4.5	--
Thermal Energy (Btu per pound of Aluminum)	5,500	5,500	3,500	35,000
Carbon	0.42 lb Petroleum Coke 0.11 lb Coal, Pitch	0.42 lb Petro- leum Coke 0.11 lb Coal, Pitch	0.9 gal Fuel Oil	1.2 lb Coke (1.7 lb of SiO_2 , also)

Source: T. Beck, Final Report on Energy Efficiency
of Industrial Electrochemical Processes
ANL/OEPM-77-2, January 1977.

2. Foreign Companies

a. Inert Anode. Alusuisse, Ltd., (Switzerland) has patented an inert non-carbon electrode for use in Hall-Héroult reduction cells. If a suitable inert cathode were developed (graphite or TiB_2), the inert anode could be used in a bipolar electrode. The advantages of this arrangement are greater compactness and less voltage drop.

b. Subhalide Process. Alcan Aluminum (Canada) spent \$40 million on this process, which was tested in a 5,000 ton-per-year pilot plant. The plant was shut down in 1968 because of stress corrosion problems. Bauxite and coke are reacted in an electric arc furnace at $2,000^{\circ}C$ to produce a crude alloy of aluminum, iron, silicon, titanium, and carbon. This alloy is reacted with aluminum trichloride to produce aluminum monochloride vapor. The vapor is cooled to decompose it into aluminum and aluminum trichloride. A major drawback to this process is the high electrical energy requirement of the electrical furnace (about 11 kWh/lb of aluminum metal produced).

c. Other Investigations. In the USSR the following processes are under investigation (9):

- (1) Electrolysis of aluminum trichloride
- (2) Thermal reduction of ore to produce alloys of aluminum and silicon, titanium, and iron.

F. Economic Evaluation

1. Production Costs

The cost of producing aluminum ingot (primary aluminum) can be divided into two components: direct costs and return on capital investment. Direct cost items include raw materials, energy, labor, and overhead. Return on investment per pound of aluminum is calculated by amortizing the total plant investment (or capital cost) over the service life and dividing this annual charge by annual production. In a recent study, (The World Metals Economy to 1990) Chase Econometrics estimated the elements of production cost for primary aluminum in 1979 and projected them to 1985. Tables II-8 and II-9 show these production costs by element. This analysis considered both extraction of alumina from bauxite as well as reduction of the alumina into aluminum metal. All figures are in 1979 dollars. The 1979 production costs assume a Hall-Héroult process operating at 7.2 kWh/lb. The 1985 costs assume a Hall-Héroult process operating at 6.8 kWh/lb.

TABLE II-8. PRODUCTION COSTS FOR PRIMARY ALUMINUM
STARTING WITH BAUXITE

(Cents per Pound)

<u>Cost Element</u>	<u>1979</u>	<u>1985</u>
Electricity	19.8 ¢	31.0 ¢
Bauxite	6.7	11.2
Direct Labor	4.5	6.2
Maintenance	4.3	6.5
Administrative	3.4	4.7
Fuel Oil	2.4	4.7
Natural Gas	0.6	1.2
Sodium Hydroxide	2.4	2.9
Other Materials	4.2	5.8
Delivery	<u>0.9</u>	<u>1.2</u>
Total Direct Cost	49.2	75.4
Capital Recovery (at 12.5%)	<u>17.8</u>	<u>25.8</u>
Total (¢ per pound)	67.0 ¢	101.2 ¢

*In 1979 dollars

Source: Chase Econometrics, The World Metals Economy in 1990.

TABLE II-9. PRODUCTION COSTS - STARTING WITH ALUMINA

<u>Element</u>	<u>Quantity</u>	<u>Price</u>	<u>¢/lb.</u>
Electricity	7.2 kWh	\$.0265/kWh	19.1
Natural gas	.002 MMBtu	\$2.50/MMBtu	0.5
Petroleum & pitch coke	0.52 lb	\$.115/lb	6.0
Alumina	1.93 lb	\$.07/lb	13.5
Direct labor			4.5
Administrative			3.4
Maintenance			4.3
Delivery			0.9
Capital recovery			<u>15.6</u>
Total			67.8¢/lb

Capital recovery is based on a capital cost of 12.5 percent, and a plant investment cost of \$2,000 per annual ton of capacity (for a reduction plant). Electricity constitutes 29.6 percent of the 1979 production cost and 30.6 percent of the 1985 projected production cost. Raw materials constitute approximately 20 percent in both 1979 and 1985.

The unit prices used in the Chase Econometrics analysis are averages. There is considerable variation in the price of electricity among aluminum plants. The analysis uses an average price of \$.0265 per kWh for 1979 and \$.044/kWh for 1985. However, aluminum producers in the Pacific Northwest, who buy power from the Bonneville Power Administration (BPA) under long-term contract, paid \$.003 per kWh until December, 1979. Since then, BPA rates for aluminum smelters have increased to \$.006 per kWh. When these long-term contracts expire (beginning in 1983), the BPA will undoubtedly raise these rates considerably. The new rate will probably be approximately \$.014/kWh (14). Though this action will add \$.08 to the price per pound of aluminum ingot, it is still far less than the average electricity price of \$.03 paid by industrial users in 1979 (15). Electricity sold to industrial users is projected to rise to a nationwide average of \$.0338/kWh in 1985, \$.0358/kWh in 1990, and \$.0418/kWh in 1995 (all in 1978 dollars) (16).

2. Domestic Aluminum Production and Foreign Competition

At present, primary aluminum production in the United States is not threatened by foreign competition. Imports of aluminum ingot, which made up 11 percent of total domestic aluminum consumption in 1979, did not substitute for domestic production, but rather supplemented it. This was because the growth in U.S. demand for aluminum has exceeded available domestic production capacity.

The worldwide distribution of planned smelting capacity, illustrated in Figure II-3, is one indication of the United States' future competitive position with foreign aluminum producers. In spite of the rising electricity costs in the United States, aluminum corporations are still planning to construct over 27 percent of the worldwide smelting capacity in the United States. If all of the planned capacity is built, the United States will have the same percentage of world aluminum capacity in 1985 as it does now (27.6 percent). However, the shortfall between domestic consumption and production will continue if aluminum demand grows at the 4 to 5 percent annual rate that many analysts forecast. This is because the 799,000 tons/year of planned capacity between 1980 and 1985 will sustain only a 2.8 percent annual growth rate.

Figure II-3. Worldwide Distribution of Planned Aluminum Smelting Capacity
(000 Tons/Year Capacity)

The most significant impact on worldwide aluminum supplies over the next 10 years will clearly be made by Australia. Australia is already the world's largest single supplier of bauxite ore (36 percent) and alumina (28 percent), and has abundant reserves of steam coal for electric power generation. Australia exported 89,000 tons of aluminum ingot in 1979. As a result of its rapidly expanding smelting capacity, Australia plans to increase exports to one million tons by 1985 and to 2 million tons by 1990. Most of the exported aluminum is expected to go to Japan and Asian markets. The potential for Australian exports to the United States depends on the cost of shipping and the market prices of aluminum on the U.S. West Coast and in Australia's other potential aluminum markets.

Other countries that may supply primary aluminum to the U.S. market over the next 20 years are Canada, Brazil, and Ghana. Brazil, which has abundant bauxite reserves, expected to export over 500,000 tons/year by the late 1980s. Canada, from which the United States already imports aluminum ingot, is developing surplus electric power capacity and is expanding its aluminum smelting facilities by 189,000 tons/ year over the next five years.

Ghana has both hydroelectric potential and extensive bauxite reserves. However, the degree to which aluminum production in lesser developed countries in South America and Africa will affect the American aluminum industry is uncertain at this time.

3. United States Supply and Demand for Aluminum: 1979 and 2000

Figure II-4 illustrates the supply and demand pattern for the U.S. aluminum industry in 1979. Total U.S. consumption (6.9 million tons) was satisfied by three sources:

- (a) U.S. primary metal production, 5.05 million tons (also see Figure II-2)
- (b) Net imports of aluminum ingot, 0.35 million tons (i.e., gross imports minus exports)
- (c) Net domestic secondary (scrap) recovery, 1.50 million tons (i.e., gross secondary minus exports).

The U.S. Bureau of Mines has forecast a scenario for the U.S. primary aluminum industry in the year 2000 (18). The Bureau projects that demand for primary aluminum will grow at an average rate of 5.5 percent per year between 1979 and the year 2000. At this growth rate, annual demand in 2000 will

Figure II-4. The U.S. Aluminum Industry: Supply and Demand, 1979 Pattern
(All values are million short tons)

be over 16 million tons. This demand is likely to be met by the following sources:

- (a) Aluminum smelted from U.S.-mined bauxite: two million tons (based on proven reserves)
- (b) Aluminum smelted from 22 million tons of imported bauxite (alumina extracted domestically): five million tons (based on projected expansion of alumina extraction facilities)
- (c) Aluminum smelted from 16 million tons of imported alumina: eight million tons (primary sources of imports - Australia)
- (d) U.S. imports of primary aluminum: approximately one million tons (to make up the deficit)
- (e) Total: 16 million tons.

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III. CHLOR-ALKALI

A. Chlor-Alkali Industry in the United States

Three major products are involved in the chlor-alkali industry: the co-products chlorine and caustic soda, and soda ash. Chlorine and caustic soda are commercially produced in an electrolytic process. Soda ash is either recovered from trona ore or synthesized from salt and limestone. Since the objective of this project is to investigate the potential for reducing the electrical power consumption by electrolysis, the production of soda ash will not be considered. Thus, chlor-alkali will refer to the chlorine and caustic soda industry.

Table III-1 shows the U.S. chlorine production and capacity for the past decade. The operating rate for each year is also shown. As can be seen, the estimated 1979 production volume was 12.0 million tons of chlorine. The total capacity reached by the beginning of 1980 was about 14.2 million tons/year. Chlorine production is expected to increase three to four percent, to about 12.5 million tons in 1980 (2).

The major producers of chlorine and caustic soda in the United States are shown in Table III-2. Table III-3 shows the total number of companies and plants producing chlorine and shows the number of plants using each production cell type. Although many cell types are used, the greatest number of plants use either diaphragm and/or mercury cells. Mercury cells account for over 40 percent of the total world production of chlorine. Diaphragm cells are predominantly used for producing chlorine in the United States. Of about 60 plants producing 95 percent of the chlorine and caustic output in 1979, 32 used diaphragm cells, which accounted for 43 percent of capacity, and 8 more plants were partially converted to diaphragm cells, accounting for another 37 percent of capacity (4). Despite the higher energy efficiency and lower energy use for mercury cells, which rapidly increased their early use, environmental problems associated with the loss of mercury have discouraged the use of mercury cells for chlorine production in the past decade. This is illustrated in Table III-4, which shows the percentage of chlorine production capacity historically held by each cell type. Table III-5 shows the location, by city and state, of all of the chlorine plants in the United States, listing the types of cells each plant uses.

TABLE III-1. U.S. CHLORINE PRODUCTION AND CAPACITY

Year	Capacity (short tons/day)	Total Production (short tons)	Average (tons/day)	Operating Rate (%)
1970 ^a	28,276	9,763,702	26,750	94.6
1974	30,310	10,753,109	29,461	97.2
1975	34,010	9,165,125	25,115	73.8
1976	35,037	10,378,432	28,356	80.9
1977	35,729	10,573,014	28,967	81.0
1978 ^b	37,429(E)	10,962,064	30,033	80.2(E)
1979 ^b	38,829(E)	12,000,000(E)	32,877	84.7(E)

E = Estimate

Sources:

^aNorth American Chlor-alkali Industry Plants and Production Data Book,
January 1979. Chlorine Institute Pamphlet 10.

^bU.S. Department of Commerce, Bureau of the Census, Current Industrial
Reports, Inorganic Chemicals, January 1979 - October 1979.

TABLE III-2. MAJOR CHLORINE PRODUCERS IN U.S.

Company	1978 Production Capacity (1,000 tons/year of chlorine)
Dow Chemical	4,650 ^a
PPG Industries	1,250 ^b
Diamond Shamrock	1,234
Hooker	1,161
Olin Corporation	930
Georgia Pacific	513 ^c
BASF Wyandotte	488 ^c
DuPont	479 ^c
Vulcan Materials	410
Pennwalt Corporation	409
Stauffer Chemical	380
FMC Corporation	350
Allied Chemical	350
Kaiser Aluminum & Chemical	205
Aluminum Co. of America	200
Ethyl Corporation	176 ^d
ICI Americas	170
Linden Chemicals & Plastics	166
Weyerhaeuser Company	140
International Minerals & Chemicals	119
Goodrich Chemical	110
Shell Chemical	105
Others	403 ^d
TOTAL	14,398

Source: Chemical Week, March 14, 1979

^aChemical Week estimate

^bExcluding capacity in Puerto Rico

^cIncluding recent expansion

^dIncluding one or more plants that do not co-produce caustic

TABLE III-3. U.S. CHLORINE PRODUCERS

Companies Operating	36
Plants Operating	68
<u>Pulp Mills Producing Chlorine</u>	
Companies Operating	5
Plants Operating	6
<u>Cells</u>	
Diaphragm Cell Plants	30
Mercury Cell Plants	21
Diaphragm and Mercury Cell Plants	6
Fused Salt Cell Plants	4
HCl Electrolysis Plants	1
Diaphragm and Fused Salt Cell Plants	1
Magnesium Cell Plants	2
Diaphragm and Magnesium Cell Plants	1
Membrane Cell	--
Non-electrolytic Plants	1
Non-electrolytic and Diaphragm Cell Plants	<u>1</u>
TOTAL	68

Source: North American Chlor-alkali Industry Plants and Production Data Book, January 1979. Chlorine Industry Pamphlet 10.

TABLE III-4. U.S. CHLORINE PRODUCTION METHODS

Year	Installed Capacity (short tons/day)	Percent of Total Installed Capacity		
		Diaphragm Cells	Mercury Cells	All Other
1946	4,012	88.6	4.3	7.1
1956	5,580	81.6	12.4	6.0
1962	14,697	76.2	18.5	5.3
1966	18,939	69.7	26.5	3.8
1970	28,276	69.6	27.2	3.2
1975	34,010	73.4	21.8	4.8
1976	35,037	73.7	21.4	4.9
1977	35,729	74.4	20.9	4.7
1978	37,429(E)	74.3	20.3	5.4

E = Estimate

Source: North American Chlor-alkali Industry Plants and Production Data Book, January 1979. Chlorine Industry Pamphlet 10.

TABLE III-5. CHLORINE PLANTS IN THE UNITED STATES
(NOT INCLUDING PLANTS UNDER CONSTRUCTION)

State & City	Producer	Year Built*	Cells	Containers Filled	Notes
Alabama					
Le Moyne	Stauffer Chemical Company	1965	De Nora 22 x 5 (merc.)	- - S B 1	
McIntosh	Olin Corporation	1952	Olin E8 (merc.), Hooker H4 (diaph.) ('77-'78)	- - S B 1	
Mobile	Diamond Shamrock Corp.	1964	De Nora 18 x 4 (merc.)	- - S - 1	
Muscle Shoals	Diamond Shamrock Corp.	1952	De Nora 24 x 2M (merc.)	- - S B 3	
California					
Pittsburg	Dow Chemical USA	1917	Dow (diaph.)	- - S - 1	
Delaware					
Delaware City	Diamond Shamrock Corp.	1965	De Nora 18 x 4 (merc.)	- - S - 3	
Georgia					
Augusta	Olin Corporation	1965	Olin E11F (merc.)	- - S - 1	
Brunswick	Allied Chemical Corp.	1957	Solvay V-100 (merc.)	- - S - 1	
Brunswick	Brunswick Chemical Co.	1967	Hooker HC4B (diaph.)	- - - - 1,7	
Illinois					
Sauget	Monsanto Company	1922	De Nora 18 x 6 (merc.)	- - S - 3	
Indiana					
Mt. Vernon	General Electric Co.	1976	Hooker H2A (diaph.)	- - - - 1	
Kansas					
Wichita	Vulcan Materials Co.	1952	Hooker HC3BT, H4 ('75) (diaph.)	C T S - 1	
Kentucky					
Calvert City	B.F. Goodrich Chemical Corp.	1966	De Nora 24H5 (merc.)	- - - - 1	
Calvert City	Pennwalt Corp.	1953	Olin E11F (merc.) ('67)	- - S B 3	
Louisiana					
Baton Rouge	Ethyl Corporation	1938	Downs (fused salt) Hooker S3D (diaph.)	- - S - 1,4	
Baton Rouge	ICI Americas, Inc.	1937	Hooker S4B (diaph.) ('68)	- - S - 1	
Geismar	BASF Wyandotte Corp.	1959	Diamond MDC41 (diaph.), Uhde 30 sq. m. (merc.) ('64), Hooker H2, HC4BT (diaph.) ('69)	- - S - 1	
Geismar	Vulcan Materials Co.	1976	Diamond MDC55 (diaph.)	- - - - 1	
Gramercy	Kaiser Aluminum & Chemical Corp.	1958	Hooker HC3B, HC3C (diaph.)	- - S B 1	
Lake Charles	PPG Industries, Inc.	1947	Columbia N 1, Hooker S3A (diaph.) De Nora 48H5 (merc.) ('69), Glanor 1144 (diaph.) ('77)	- - S B 1	
Plaquemine	Dow Chemical USA	1958	Dow (diaph.)	- - S - 1	
Plaquemine	Georgia-Pacific Corp.	1975	Hooker H4 (diaph.)	- - S - 1	
St. Gabriel	Stauffer Chemical Co.	1970	Uhde 30 sq. m. (merc.)	- - S B 1	
Taft	Hooker Chemical Corp.	1966	Hooker HC4B, C60, HC80, H4 ('75) (diaph.)	- - S - 1	
Maine					
Orrington	IMC Chemical Group, Inc.	1967	De Nora 24H5 (merc.)	- - S - 1	
Michigan					
Midland	Dow Chemical USA	1897	Dow (diaph.)	- - S - 1	
Montague	Hooker Chemicals & Plastics Corp.	1954	Hooker HC3B (diaph.)	- - S - 1	
Wyandotte	BASF Wyandotte Corp.	1938	Hooker HC3A (diaph.)	- - S - 1	
Wyandotte	Pennwalt Corp.	1898	Diamond DS43 (diaph.) ('60)	C T S - 1	
Mississippi					
Vicksburg	Vicksburg Chemical Co.	1962	None	C T S - 6	
Nevada					
Henderson	Stauffer Chemical Co. of Nevada, Inc.	1942	Diamond MDC29 (diaph.) ('76)	- - S - 1	
New Jersey					
Linden	Linden Chemicals & Plastics, Inc.	1956	BASF - Krebs (merc.) ('69) Krebs (merc.) ('63)	- - S - 1	
New York					
Niagara Falls	E.I. du Pont de Nemours & Co. Inc.	1898	Downs (fused salt.)	- - - - 4	
Niagara Falls	Hooker Chemicals & Plastics Corp.	1898	Hooker H4 (diaph.) ('74,'78)	- - S - 1	
Niagara Falls	Hooker - IMC Joint Venture	1971	Uhde 20 sq. m. (merc.)	- - S - 2	
Niagara Falls	Olin Corporation	1897	Olin E11F (merc.) ('60)	- - S - 1	
Syracuse	Allied Chemical Corp.	1927	Solvay S60 (merc.) ('53) Hooker HC4B (diaph.) ('68, '77)	- - S - 1	

TABLE III-5. (CONTINUED)

State & City	Producer	Year Built*	Cells	Containers Filled	Notes
North Carolina					
Acme	Allied Chemical Corp.	1963	Solvay V-200 (merc.)	- - S -	1
Canton	Champion International Corp.	1916	Hooker S1 (diaph.)	- - - -	1,7
Ohio					
Ashtabula	IMC Chemical Group, Inc.	1963	Olin E11F (merc.)	- - S -	2
Ashtabula	RMI Company	1949	Downs (fused salt)	- - S -	4
Barberton	PPG Industries, Inc.	1936	Columbia (diaph.)	- - S -	1
Oregon					
Portland	Pennwalt Corp.	1947	Diamond, DS41, DS43 (diaph.) ('67)	C T S B	1
Tennessee					
Charleston	Olin Corporation	1962	Olin E11F, E812 (merc.)	- - S B	1
Memphis	E.I. du Pont de Nemours & Co., Inc.	1958	Downs (fused salt)	- - S -	4
Texas					
Baytown	Mobay Chemical Corp.	1972	Uhde (HCl)	- - - -	5
Corpus Christi	E.I. du Pont de Nemours & Co., Inc.	1974	Kelchlor, Diamond MDC55 (diaph.)	- - - -	1,10
Deer Park	Diamond Shamrock Corp.	1938	Diamond MDC22 (diaph.)	- - S B	1
Deer Park	Shell Chemical Co.	1966	De Nora 18 SGL (merc.)	- - - -	1
Denver City	Vulcan Materials Co.	1947	Hooker HC-48T (diaph.)	- - - -	1
Freeport	Dow Chemical USA	1940	Hooker S1 (diaph.)	- - - -	1
Houston	Ethyl Corporation	1952	Dow (diaph.), Dow (magnesium)	- - S -	1,9
Houston	Ethyl Corporation	1952	Downs (fused salt)	- - S -	4
Houston	Champion International Corp.	1936	Hooker S1 (diaph.)	- - - -	1,7
LaPorte	Diamond Shamrock Corp.	1974	Diamond MDC 29 (diaph.)	- - S -	1
Point Comfort	Aluminum Co. of America	1966	De Nora 24X5, 24H5 (merc.)	- - S B	1
Port Neches	Jefferson Chemical Co., Inc.	1959	Hooker S3B (diaph.)	- - - -	1
Snyder	American Magnesium Co.	1969	VAMI (magnesium)	- - - -	9
Utah					
Rowley	NL Industries, Inc.	1977	Modified IG Farben (magnesium)	- - S -	9
Virginia					
Hopewell	Hercules, Inc.	1939	Hooker HC3 (diaph.)	- - S -	1
Washington					
Bellingham	Georgia-Pacific Corp.	1965	De Nora 18 x 4 (merc.)	- - S B	1,7
Longview	Weyerhaeuser Company	1957	Diamond MDC29 (diaph.) ('75)	- - S -	1,7
Tacoma	Hooker Chemicals & Plastics Corp.	1929	Hooker S1, S3 (diaph.)	- - S B	1
Tacoma	Pennwalt Corp.	1929	Glanor 1144 (diaph.)	C T S -	1
West Virginia					
Moundsville	Allied Chemical Corp.	1953	Solvay S60 (merc.)	- - S B	1
New Martinsville	PPG Industries, Inc.	1943	Columbia N 1, N 3, N 6 (diaph.)	- - S B	1
So. Charleston	FMC Corporation	1916	Uhde 20 sq. m. (merc.) ('58)	- - S B	1
			Hooker HC3B (diaph.) ('73)	- - S B	1
			Hooker H1 (diaph.) ('73)	- - S B	1
Wisconsin					
Green Bay	Fort Howard Paper Co.	1968	Hooker HC3C (diaph.)	- - - -	1,7
Port Edwards	BASF Wyandotte Corp.	1967	De Nora 24H5 (merc.)	- - S -	1
PUERTO RICO					
Guayanilla	PPG Industries (Caribe)	1971	De Nora 27M2 (merc.)	C T - -	1,8

TABLE III-5. (CONTINUED)

NOTES AND SYMBOLS

NOTES:

1. Electrolytic plant producing caustic soda, chlorine and hydrogen from brine
2. Electrolytic plant producing caustic potash, chlorine and hydrogen from brine
3. Electrolytic plant producing caustic soda, caustic potash, chlorine and hydrogen from brine
4. Electrolytic plant producing metallic sodium and chlorine from molten salt
5. Electrolytic plant producing chlorine and hydrogen from hydrochloric acid
6. Non-electrolytic plant producing chlorine and potassium nitrate
7. Pulp Mill
8. Not operating
9. Electrolytic plant producing magnesium and chlorine from molten magnesium chloride
10. Non-electrolytic plant producing chlorine by oxidation of HCl

SYMBOLS

- M Chlorine Institute Member
C Cylinders
T Ton Containers
S Single Unit Tank Cars
B Barges

- * Refers to year chlorine production started at location
** Dow Freeport includes both Texas and Oyster Creek divisions

Source: North American Chlor-alkali Industry Plants and Production
Data Book, January 1979. Chlorine Industry Pamphlet 10.

Although growth of the chlor-alkali industry has slowed, there are new plants being added or planned for the near future. Table III-6 shows the capacities and the projected completion dates of new facilities since 1978. Over the next four years very little expansion is anticipated and the expected rate of capacity increase will be about 2.6 percent/year (1). Many organizations within the chemical and chlor-alkali industries have projected annual chlorine growth rates ranging from three to seven percent/year for the time period from 1980 to 2000. These are tabulated in Table III-7. For the purposes of this project, HAI has chosen a moderate growth rate of 3.5 percent/year from 1980 to 2000. This growth rate will result in a gradual increase in the operating rate of chlorine plants, bringing closer into balance chlorine supply and demand.

The major end uses of chlorine and caustic soda are shown in Tables III-8 and III-9 with their shares of production and projected growth rates (1). As seen in the table, the major use of chlorine is in the production of chemicals, many of which are hydrocarbon derivatives. In chemical manufacture, chlorine is often used in an intermediate reaction, and does not remain in the final product. Two factors which revolve from this and which help to stifle chlorine growth, are the high cost of hydrocarbons feedstocks and the expense of pollution control in handling chlorine after its

B. The Foreign Chlor-Alkali Industry

Table III-10 shows the world's chlorine production per year. It includes almost all countries with a requirement of elementary chlorine for their chemical industry or other uses. Some industrialized countries, such as Great Britain, will not publish their production figures because they do not wish to give any information to competitors.

Table III-11 is an assessment of further growth of the chlor-alkali industry. The average annual growth rate for 1965 to 1970 was 9.3 percent. However, the growth rate slowed at the beginning of the Seventies. Percent growth in the underdeveloped countries or third world countries is expected to increase at a higher rate than in more developed countries. As more countries try to produce chemicals to meet their own demand, there will be fewer exports for the developed countries and hence, a lower growth rate.

In 1975, the world's chlorine production was 22,496,000 tons (Table III-10). Production for 1978 of various chlorine producing nations was as follows: (15)

TABLE III-6. NEW OR EXPANDED CHLORINE PLANTS PLANNED OR UNDER CONSTRUCTION

Producer and Location	Cell Type	Added Capacity (tons/day chlorine)	Status	Completion Date
1. Convent Chemical Co., (B.F. Goodrich & Bechtel) Convent, LA	Diamond MDC 55	800 New Plant	Underway	Early 1981
2. BASF Wyandotte Corp. Geismar, LA	Diaphragm	68.5 Expansion	Completed	1st Quarter 1979
3. PPG Industries Lake Charles, LA	Glanor® 1144 Bipolar diaphragm	750 Expansion	Underway	2nd Quarter 1980
4. Georgia Pacific Corp. Plaquemine, LA	Hooker H-4	240 Expansion	Completed	Early 1979
5. Fort Howard Paper Co. Muskogee, OK	Hooker MX membrane	12.5 New Plant	Underway	4th Quarter 1979
6. Pennwalt Corp. Portland, OR Tacoma, Washington		100 Expansion 50 Expansion	Underway Underway	4th Quarter 1979 4th Quarter 1979
7. Dow Chemical USA Freeport, TX		Expansion as needed to main- tain company share of 1/3 of total U.S. capacity	Continuing	1980-1981
8. Diamond Shamrock Corp. LaPorte, TX		200 Expansion	Completed	1979
9. Hooker Chemical and Plastics Tacoma, WA	Hooker H-4	275 Expansion	Engineering	Mid 1980

Source: North American Chlor-alkali Industry Plants and Production Data Book, January 1979, Chlorine Institute Pamphlet 10, Updated.

TABLE III-7. U.S. CHLORINE PRODUCTION TREND

Reference	Study	Period Covered	Assumed Growth Rate (%/yr)
5	Industrial Electrolytic Division of the Electrochemical Society	1978-1985	5.0
6	Kirk-Othmer, Encyclopedia of Chemical Technology	1975-1985	Low 3.0 High 7.0 Probable 5.0
7	PPG Industries, Inc.	1976-1980	Low 3.5 High 5.5 Probable 4.3
4	U.S. Department of Commerce	1979-1984	4.0
8	Hooker Chemicals	1976-1985	5.0
9	Fluor Corporation	1980-1987	4.0
10	Hooker Chemicals	1980-1985	3.5
11	DuPont	1980-1985	3.0
12	Chemical Purchasing	1978-1982	4.0
13	PPG Industries, Inc.	1980-1985	3.1
14	Hooker Chemicals and Plastics Corp.	1985-2000	3.5-3.8
	Hittman Associates, Inc. Estimate		3.5

TABLE III-8. CHLORINE END USES

	Share (%)	Growth Rate (%/year) 1978-1984
Plastics	20	6
Water Treatment	6	5
Inorganic Chemicals	11	4
Organic Chemicals	44	3
Pulp & Paper	13	1
Miscellaneous	6	3
Average		3.6
Historical Growth		6.1

TABLE III-9. CAUSTIC SODA END USES

	Share (%)	Growth Rate (%/year) 1978-1984
Inorganic Chemicals	11	5.5
Organic Chemicals	41	5.5
Pulp & Paper	17	4
Petroleum	4	6
Soaps & Detergents	4	2
Textiles & Rayon	6	1.5
Aluminum	6	1
Miscellaneous	11	5.5
Average		4.6
Historical Growth		5.8

TABLE III-10 WORLD CHLORINE PRODUCTION

(1,000 tons)

	1965	1970	1974	1975
Europe				
FRG	1,081	1,726	2,725	2,206
Benelux	588	677	790	300
France	588	1,027	1,344	1,047
Belgium/Luxembourg	90			
Netherlands	170			
Italy	607	887	1,023	892
U.K.	792	893	685	862
Denmark	4	11	9	12
EC	3,332	5,221	6,576	5,779
Norway	60	71	61	40
Sweden	221	334	419	350
Finland	108	155	200	165
Switzerland	30	60	130	120
Austria	30	47	100	80
Portugal	5	11	15	12
Spain	78	167	326	369
Turkey	15	15	18	15
Greece	2	20	32	30
Other Europe	535	880	1,301	1,181
Yugoslavia	38	44	48	55
Soviet Union	900	1,400	1,700	1,700
Poland	97	188	245	265
USSR	155	170	58	57
Hungary	15	15	14	13
Romania	100	160	222	220
Bulgaria	5	5	10	10
GDR	325	350	400	360
Eastern Europe	1,630	2,332	2,697	2,680
Europe Without Eastern Bloc	3,867	6,101	7,877	6,960
Europe With Eastern Bloc	5,497	8,433	10,574	9,610
Africa				
Morocco		6	8	5
Algeria	2	2	9	9
Tunisia		3	3	3
Egypt	5	5	13	13
Sudan		3	3	3
Zaire Katanga				
Angola		3		
Kenya		2	3	2
Rhodesia				
Republic of South Africa	45	50	55	50
Africa	52	76	101	91

TABLE III-10. (CONTINUED)

(1,000 tons)				
	1965	1970	1974	1975
Asia				
Iraq	--	2	3	2
Iran	3	5	10	8
Israel	9	18	25	20
Jordan	--	3	3	3
Saudi Arabia	--	--	--	--
Kuwait	--	1	4	4
Pakistan	4	20	33	35
India	50	147	148	150
Sri Lanka	1	1	2	2
Thailand	6	10	80	65
Vietnam	2	10	15	12
Indonesia	1	3	5	4
Malaysia	--	6	8	6
Singapore	--	5	8	7
Philippines	10	10	20	15
Peoples Republic of China	--	15	30	30
South Korea	7	15	36	30
Japan	1,246	2,309	2,810	2,610
Taiwan	61	100	135	120
Hong Kong	--	5	8	7
Asian Countries	1,400	2,685	3,383	3,130
North America				
U.S.A.	5,912	8,850	9,633	8,185
Canada	516	763	953	749
North America	6,428	9,613	10,586	8,934
Central and South America				
Mexico	46	80	100	85
Rep. Honduras	--	3	4	3
Nicaragua	--	3	4	3
Cuba	--	3	4	3
Colombia	32	30	40	30
Venezuela	10	10	20	18
Ecuador	--	3	4	3
Peru	5	34	70	60
Brazil	40	100	300	244
Chile	6	25	40	35
Bolivia	--	--	8	7
Uruguay	--	10	12	10
Argentina	45	75	90	85
Central and South American Countries	184	376	696	586
North and South America	6,612	9,989	11,282	9,520
Australia and New Zealand	53	90	111	115
Source: Chemische Industrie International, 1/77.				

TABLE III-11. WORLD CHLORINE PRODUCTION GROWTH

(1,000 tons)

	Production 1965	Share (%) 1965	Production 1970	Av. Annual Growth Rate (%) 1965-70	Production 1974	Av. Annual Growth Rate (%) 1970-71	Production 1975	Share (%) 1975	Av. Annual Growth Rate (%) 1970-75	Av. Annual Growth Rate (%) 1975-80
Europe (West)	3,867	28	6,101	9.5	7,877	6.6	6,960	31	2.7	5.4
Europe (East)	1,630		2,332		2,697		2,680			
Africa . . .	52	0.4	76	7.9	101	7.4	91	0.4	3.7	28.0
Asia	1,400	10	2,685	13.9	3,383	5.9	3,130	14	3.1	10.7
North America	6,428	47	9,613	8.4	10,586	2.4	8,934	40	1.5	6.7
Central and South America	184		376		696		586			
Australia . .	53	0.4	90	11.2	111	5.4	115	0.5	5.0	26.0
	13,614	100	21,273	9.3	25,451	4.6	22,496	100	1.1	7.8

Source: "World Chlorine Production Will Rise at a Steady Pace," *Chemische Industrie International*, 1/77.

1978 Production

(1,000 Tons)

United States	10,959	
Canada	1,037	
Mexico	193	
Brazil	554	
FRG	3,011	
USSR	3,040	
Bulgaria	112	} Eastern Europe
Czech	340	
East Germany	456	
Hungary	169	
Poland	509	
Romania	880	
China	1,804	5,506
Japan	716	

1. Canada

The chlor-alkali industry is essential to the development of the Canadian economy because of its contribution to a variety of industrial sectors. The pulp and paper industry dominates the chlorine market. Chlorine and caustic soda production began in Canada in 1912 at Windsor, Ontario, utilizing the vast salt deposits in the area. There are presently 15 producing units with a total production capacity of 1.4 million tons of chlorine and 1.5 million tons of caustic soda. Until 1972, most Canadian chlor-alkali units used the mercury cell process. Since 1972, there has been a move to diaphragm cells, due to pressure from environmentalists to reduce the possibility of mercury pollution. Older plants are either being converted or shut down (16).

The operation of chlor-alkali units is very energy intensive and most are located close to the source of electrical power rather than the raw materials. Because electrical energy in Canada is lower in cost than in other countries, the chlor-alkali industry has sustained a growth rate of over six percent during the past 16 years. Normally, Canada is a net exporter of chlorine and a net importer of caustic soda.

There are two membrane cell plants operating in Canada. Hooker Chemicals commercialized the first membrane cell installation at the Dryden, Ontario, plant of Reed Ltd. The production capacity of this plant is 45 tons per day. The second plant, operated by Saskatoon Chemicals, a division of Prince Albert Pulp and Paper Co., uses the ion exchange

membrane technology developed by the Asahi Chemical Industry of Japan, and has a production capacity of 85 tons per day of chlorine. Energy consumption of the facility is 20 percent less than any comparable plant (3).

The total Canadian chlorine production for recent years is given below:

<u>Year</u>	<u>Short Tons/Day</u>
1974	1,052,294
1975	838,349
1976	990,245
1977	979,209

In Canada, the schedule for expansion and modernization in 1979 was as follows:

<u>Location</u>	<u>Producer</u>	<u>Project</u>
Alberta Fort Saskatchewan	Dow Chemical of Canada	Expansion 900 TPD Dow (Diaph.)
New Brunswick Nackawic	St. Anne-Nackawic Pulp & Paper Co.	30 TPD Asahi Chemical (Membrane)
Quebec Becancour	Canadian Industries, Ltd.	Expansion 385 to 770 TPD \$100 million

The Canadian Industries, Ltd., plant features a new cell line using 112 ICI-Solvay diaphragm cells. The manufacturer claims that the cells yield 50 percent more output than older ones because of a higher current density. At present, Diamond Shamrock has three active projects underway using membrane technology in Canada (17).

The market share of chlorine and caustic soda is given in Figures III-1 and III-2 (10).

2. Federal Republic of Germany

In the Federal Republic of Germany the chlorine production growth rate after 1971 exceeded that of the chemical industry as a whole. PVC accounts for 20 percent of the market share. Exports of PVC exceeded imports for the first

Figure III-1. Market Shares for Chlorine (16)

Figure III-2. Market Shares for Caustic Soda (16)

time in 1973 and have been growing since then. In contrast, the number of exports of sodium hydroxide has always exceeded the number of imports. German chlorine production for recent years is as follows:

<u>Year</u>	<u>German Chlorine Production</u> (Short Tons/Year)
1974	2,725,000
1975	2,296,000
1976	2,808,669
1977	2,807,658
1978	3,010,860

About 85 percent of the chlorine produced in 1975 was manufactured by the amalgam process and 15 percent by the diaphragm process. The average power consumption for the mercury process was 3,600 kWh per ton, and 3,300 kWh per ton for the diaphragm process. Thus, the total power consumption for chlorine production was about 8.2×10^9 kWh (18). This represents 22 percent of the entire electric power consumption of the chemical industry. Most of the mercury plants employ Uhde, IG Uhde, or BASF cells. Types of diaphragm cells used are Diamond-Shamrock, Solvay, Hooker, Dow, and ICI. Research and development of membrane cell technology has been initiated by Uhde.

3. Japan

Japan's Ministry of International Trade and Industry predicts that a chlorine shortage in Japan will end this year, now that the demand for caustic soda has improved. This rise in chlorine output should slow Japanese imports of ethylene chloride (used for PVC), which climbed from 193,329 metric tons in 1978 to 353,500 metric tons in the first 10 months of 1979.

The Asahi Chemical Company membrane chlor-alkali process is installed at the following two locations in Japan (5):

Asahi Chemical Co.	Nobeoka Factory Miyazaki Pref. Japan	80,000 tons/year
Denki Kagaku	Ohmi Factory, Niigata Pref. Japan	60,000 tons/year

Both factories use the perfluorocarboxylic acid membrane, developed by Asahi.

The Asahi Glass Company started up a 24,000 tons/year membrane cell plant at its Kansai factory (Hyogo Pref.), Japan, in August 1978. Olin Corp. (Stamford, Connecticut), and Asahi Glass (Tokyo), have signed an eight-year agreement under which Asahi will supply membranes to Olin, subject to Japanese government permission (19). Olin will test the membranes in its chlor-alkali cells. The Tokuyama Soda Company is the third Japanese firm to succeed in the ion exchange membrane process technology and operation. Diamond Shamrock has one active project underway using membrane technology in Japan.

C. Chlorine Production Process Parameters

The principal process by which chlorine is generated is the electrolysis of brine. By dissolving salt in water to form brine, the salt crystals decompose into sodium and chloride ions which become mobile and thereby readily accessible. When an electric current is passed through the brine from immersed electrodes, the positive sodium ions move toward the negative electrode and the negative chlorine ions move toward the positive electrode. The chlorine ions pair off to produce chlorine gas. Sodium ions combine with hydroxyl ions, generated by the concurrent electrolysis of water, to form sodium hydroxide (caustic soda). Hydrogen gas is also formed as a by-product of the electrolysis of water. The caustic soda must be kept separate from the chlorine gas to prevent reaction. This is achieved by (1) the use of separators in diaphragm or membrane cells, or (2) mercury cells which allow the formation of an amalgam with mercury for subsequent formation of caustic.

Theoretically, 1.13 tons of sodium hydroxide (dry basis) are produced with every ton of chlorine (20). This forms the basis of the unit of measure for electrolytic cell products, called the Electrochemical Unit (ECU). One ECU consists of 1.1 tons of caustic and one ton of chlorine.

There are several variables affecting the energy and power requirements of electrolytic cells. Some of these variables are common to all three cell types, and others are pertinent to only one or two. The following formula describes the performance of a chlor-alkali electrolysis cell (16):

$$\text{kWh/metric ton of Chlorine} = \frac{75,600 \times \text{Cell Voltage}}{\text{Chlorine Current Efficiency (\%)}}$$

The formula shows that the performance of an electrolysis cell can be improved by decreasing the cell voltage and increasing the anode, or chlorine, current efficiency,

resulting in a lower power consumption. The chlorine current efficiency of modern cells is usually 94 to 98 percent, due to side reactions and other substances capable of being electrolyzed in the brine. Further improvement may not be possible without sacrificing some of the safety features of cell operation.

Much of the research and development over the last decade has been directed toward the reduction of cell power consumption by decreasing cell voltage. Cell voltage is made up of:

- (1) IR drop through the anode structure and base
- (2) Anode potential
- (3) Brine IR drop
- (4) Separator IR drop
- (5) Cathode potential
- (6) IR drop through the cathode structure and bus.

Table III-12 indicates the factors which influence each of these increments of cell voltage.

TABLE III-12. FACTORS INFLUENCING CELL VOLTAGE INCREMENTS

Voltage Increment	Parameter
Anode and base IR drop	Structural current density, Conductivity of materials used, Length of current path
Anode potential	Anode material, Anode configuration
Brine IR drop	Electrolysis current density, Conductivity of brine, Distance of brine gap
Separator IR drop	Electrolysis current density, Conductivity of separator, Thickness of separator
Cathode potential	Cathode material, Cathode configuration
Cathode and bus IR drop	Structural current density, Conductivity of materials used, Length of current path

It should be noted that a separator is not used in the mercury cell, and thus will have no voltage drop attributed to it.

Cell performance is affected by the structural stability of the anode when graphite electrodes are used. Small amounts of oxygen are generated by the electrolysis of the water in the brine. The oxygen tends to react with the carbon in graphite, forming carbon dioxide and wearing away the anode surface. This increases the brine gap, which increases the working voltage and reduces the effective operating area of the anode. Metal or dimensionally stable anodes (DSA) and computer-controlled brine gaps, through the use of expandable anodes, have been developed which greatly reduce these effects. With the implementation of dimensionally stable anodes, higher current densities could be used, increasing the cell capacities.

The purity of the brine affects its conductivity, which in turn, can alter the current efficiency and the voltage drop across the brine. In diaphragm cells, the current efficiency is affected by caustic concentration in the brine. The lower the caustic concentration in the brine, the higher the current efficiency. The practical limit to saving energy is reached when there is a balance between the energy saved in the cell and the additional evaporation energy required to raise the caustic concentration upon leaving the cell (20).

Concentration of sodium chloride will also affect cell performance. In diaphragm and membrane cells, the salt concentration is close to saturation, but in mercury cells the brine entering the cell contains about 25 to 26 percent NaCl by weight. The brine contains about 21 to 22 percent when it leaves the cell. Further decomposition would decrease brine conductivity (6).

The life of an asbestos diaphragm is only several hundred days, due to plugging of the surface by impurities. Modified diaphragms have been developed with double the lifetime and better capability to maintain shape in service, thus permitting the use of a smaller brine gap (20).

Cell voltage profiles incorporating dimensionally stable anodes (DSA), expandable anodes, and modified diaphragms are compared with cell voltage profiles using graphite anodes in Table III-13 (21).

TABLE III-13: CELL VOLTAGE PROFILES -
GRAPHITE ANODES VS. DSA

	Graphite Anodes Average Conditions	DSA
Anode potential	1.50 V	1.29 V
Cathode potential	1.10	1.10
IR drop of anode and cathode structures	0.50	0.17
Brine IR drop	0.50	0.23
Diaphragm IR drop	<u>0.33</u>	<u>0.30</u>
	3.93 V	3.09 V

Anodic current density at 1.2 kA/m²

Cell voltage profiles are given in Tables III-14 and III-15 for diaphragm cells using DSA at three current densities and comparing standard DSA cells and cells with modified technology (21).

TABLE III-14. DIAPHRAGM CELL VOLTAGE PROFILES USING
DSA AT THREE CURRENT DENSITIES

Anodic Current Density	1.20 kA/m ²	2.17 kA/m ²	2.40 kA/m ²
Anode potential	1.29 V	1.30 V	1.31 V
Cathode potential	1.11	1.16	1.17
IR drop of anode and cathode structures	0.12	0.21	0.23
Brine IR drop	0.23	0.44	0.49
Diaphragm IR drop	<u>0.34</u>	<u>0.66</u>	<u>0.72</u>
	3.09 V	3.77 V	3.92 V

TABLE III-15. CELL VOLTAGE PROFILE COMPARING STANDARD
DSA CELLS AND CELLS WITH MODIFIED TECHNOLOGY

Type of Diaphragm Type of Anode	Asbestos Standard	Modified Standard	Modified Expandable
Anode potential	1.31 V	1.31 V	1.31 V
Cathode potential	1.16	1.16	1.16
IR drop of anode and cathode structures	0.21	0.21	0.21
Brine IR drop	0.44	0.52	0.32
Diaphragm IR drop	0.66/3.98	0.37/3.57	0.37/3.37

Anodic current density at 2.17 kA/m²

Oxygen cathodes are being developed for use in membrane cells to replace the evolution of hydrogen with electrolytic reduction of oxygen. This may reduce the cell voltage by approximately one volt. In addition, cathode coatings have been developed for use in membrane and diaphragm cells to increase their life and reduce the cell voltage.

There is potential for reducing overall energy consumption in chlorine and caustic production through the use of cogeneration and fuel cell applications. Diaphragm and membrane plants could use cogeneration systems to supply both electrical and steam requirements, and all three plant types could use fuel cell applications for producing electrical energy from hydrogen by-product. Some chlor-alkali plants are beginning to use cogeneration, but to date none are using fuel cell applications. Research is currently being done in this area.

D. Chlorine Production Processes

In the following discussion a process description is given for each cell type, along with energy requirements, followed by recent improvements for energy reductions specific to that cell.

1. Mercury Cells

a. Process Description. The mercury cell process involves a primary electrolyzer, called the brine cell, and a decomposer. Purified, saturated brine containing approximately 25.5 weight percent sodium chloride flows through an inclined trough in the primary electrolyzer. In the bottom of the trough, beneath the brine, flows a shallow sheet of mercury, the cathode. The anode assembly, consisting of graphite or dimensionally stable anodes, is suspended above the cathode. Current flowing through the cell electrolyzes the brine, releasing chlorine at the anode and sodium at the cathode. The chlorine gas is collected above the anode assembly, and sodium combines with the mercury to form a low concentration amalgam, containing 0.25 to 0.5 weight percent sodium. The amalgam then flows to a packed-bed reactor where, upon reaction with water, hydrogen gas is liberated and sodium hydroxide is formed. The purified mercury then returns to the electrolyzer (6). A schematic of the mercury cell is shown in Figure III-3. The chlorine produced by the mercury cell is pure, but must be dried with sulfuric acid and compressed before liquefaction (22). The caustic produced has a concentration of about 50 percent by weight, with a low residual brine concentration of about 30 ppm (17).

Figure III-3. Mercury Cell Schematic

Source: Chlor-alkali Membrane Cell Set for Market, Chemical and Engineering News, March 20, 1978

The mercury cell requires a large capital investment, has high electrical energy consumption, and requires control systems for mercury emissions (17). Since no additional caustic concentration is necessary, all of the power and energy needs are electrical. Energy requirements for various types of mercury cells are given in Table III-16. Typical operating characteristics of mercury cells are given in Table III-17.

The mercury used in a mercury cell represents a significant portion (10 to 15 percent) of the total investment in the cell, and since by government decree is not considered fixed capital, it cannot be depreciated (6). Prior to government regulation, mercury losses ranged from 0.3 to 0.5 pound per short ton chlorine. Mercury was lost through the product and waste streams by vaporization caused by the high operating temperatures of the electrolyzers and decomposers (13). Recent EPA regulations limit effluent discharge to 0.28 g mercury per metric ton of product for existing plants, with an additional 50 percent reduction for new plants (23). To meet these regulations, in addition to elaborate filter systems, mercury cell plants have had to install more efficient coolers to condense mercury vapor (6).

b. Recent Mercury Cell Improvements for Energy/Power Reductions. The mercury cell does not appear to be the cell of the future. The majority of new plants which are being built, or have recently been built, incorporate either diaphragm or membrane cells. However, existing mercury cell plants will undoubtedly continue operating until deterioration. Caustic produced from amalgam is particularly suited to rayon manufacture, and as such will be in demand.

Olin Corporation has four plants using mercury cells of its own design, and has no plans for converting to diaphragm or membrane cell systems. However, its plant expansion in McIntosh, Alabama, completed in 1978, is a diaphragm cell plant and other expansions are likely to use membrane cells (24). Olin has replaced all of its carbon anodes with metal anodes, and has added computer-controlled anode adjuster systems which control the brine gap to every plant. These changes were completed in 1975 and resulted in a 10 percent reduction in energy consumption. Most other U.S. mercury plants use DeNora mercury cells. Recent improvements made by DeNora include (25):

- (1) Complete sealing of the mercury circuit to prevent escape

TABLE III-16. ENERGY REQUIREMENTS OF MERCURY CELLS

Make or Type	kWh/ton of Chlorine
Sorensen	3,180
Bitterfield	3,340-3,700
Horizontal-rectangular	2,980-3,340
Vertical	3,380-3,780
Mathieson E-4	3,400
Mathieson E-8	3,260
Solvay V-100	3,140
Solvay V-200	3,180
Uhde 10 m ²	3,120
Uhde 20 m ²	3,120
BASF-Krebs 40	3,260
BASF-Krebs 80	3,260
DeNora horizontal 14TGL	3,020
DeNora vertical FAC-17	3,100
Olin EllF	3,200
LOW	2,980
AVERAGE	3,260
HIGH	3,780

TABLE III-17. TYPICAL OPERATING CHARACTERISTICS
OF MERCURY CELLS

Rated cell capacity, ka	40 to 200
Cathode current density, amp/sq cm	1.0
Average cell voltage	4.3
Current efficiency	95
DC energy, kWh/ton	3,260
Anode life, months	10
Graphite consumption, lb/ton chlorine	5
Mercury loss, lb/ton Cl ₂	.02-.2
Cell gas analysis, percent	
Cl ₂	99
H ₂	.5
CO ₂	.5
Caustic strength, percent	50

- (2) Computerized control of the interelectrode gap, permitting a uniform distribution of current density along the cell, thus improving efficiency and prolonging anode life
- (3) Anode probes to sensor any likelihood of short circuits, thus preventing anode damage and reducing cell maintenance
- (4) Use of improved ion selective DSA which permits very high current density and longer life.

Uhde of West Germany has developed highly automated mercury cells using DSA, and new mercury cell plants are under construction. Mercury cell plants in the Soviet Union have been improved by (26):

- (1) The introduction of metallic anodes
- (2) The installation of special electromagnetic devices in the cell end boxes for the purification of mercury from ferromagnetic matter
- (3) The addition of purification, evaporation, and ion exchange facilities to eliminate mercury pollution.

The Investigación Química Industrial, S.A., of Spain has developed a new electrolytic technology combining the membrane and mercury (MEMMER) processes. In this new cell design, mercury is held in a vertical electrodic plane by the membrane. This enhances the electrodic surface, separates the cathodic and anodic products, inhibits the mercury anolyte contact, and avoids the possibility of short-circuiting. An industrial prototype cell was begun in 1979 and is undergoing testing and evaluation.

2. Diaphragm Cells

a. Process Description. The diaphragm cell process consists of electrolyzing saturated brine by placing a diaphragm between the electrodes. This retards the diffusion of hydrogen and caustic from the cathode, where they are produced, to the anode, where the chlorine is produced. Modern diaphragm cells employ vertical electrodes and an asbestos diaphragm which is vacuum-deposited on the cathode (6). Purified brine entering the anode section percolates through the diaphragm into the cathode section, liberating chlorine gas at the anode and hydrogen gas at the cathode. The cell liquor, containing about eight to ten percent caustic soda

and 14 percent sodium chloride, discharges through the cathode compartment (6,22). The caustic is normally concentrated by evaporation of water to about 50 percent NaOH by weight, and the salt is recycled to the cell (22). Figure III-4 shows a Hooker Type H4 diaphragm cell.

Power and energy requirements for diaphragm cells are electricity for electrolysis and steam for evaporation. The electrical energy requirements of different makes of diaphragm cells are listed in Table III-18. Table III-19 presents a comparison of four producers' diaphragm cells, showing the differences in operating characteristics and power consumption for each cell. Table III-20 contains typical operating characteristics of diaphragm cells (without DSA). The steam requirement for caustic evaporation to 50 percent NaOH ranges from 4,000 to 6,000 lb per ton caustic.

b. Recent Diaphragm Cell Improvements for Energy/Power Reduction. Dow Chemical, the largest producer of chlorine and caustic soda in the United States, uses diaphragm cells for nearly all of its total capacity. Little information has been published on the performance and types of Dow cells the company uses. It is known that the company will switch some or all of its capacity from graphite to metal anodes within the next six to eight years. Dow will manufacture its own metal anodes using the acquired rights to patents controlled by Diamond Shamrock. In addition, cobalt spinel anode coatings are in use in several company plants. Dow claims that results to date are highly encouraging.

Process improvements made by Hooker Chemical during 1970 to 1980 are listed in Table III-21 (27). In addition, early in 1980, the company started a cogeneration facility at Niagara Falls, New York. The plant is expected to supply 20 percent (20 to 25 MW) of the power and 100 percent of the steam to produce 800 tons per day of NaOH. The fuel is 2,200 tons per day of municipal refuse. Hydroelectric power supplies the remaining electricity which is bought from a utility.

Recent improvements by Diamond Shamrock Corporation include:

- (1) Conversion to dimensionally stable anodes resulting in a 20 percent power savings
- (2) Use of modified diaphragm cells with expandable anodes providing another 10 to 15 percent power savings. This diaphragm was first used in 1972.

Figure III-4. Hooker Type H4 Diaphragm Cell (28)

TABLE III-18. ENERGY REQUIREMENTS OF DIAPHRAGM CELLS

Make	kWh/ton of Chlorine
Hooker type S	2,320-2,700
Hooker type S-3	2,700
Hooker type H-4	2,420
Tucker-Windecker	2,560
Giordani-Pomilio	2,460-2,720
Wheeler	2,700
Dow	2,280 (est)
Vorce	2,540
Vorce double cathode	2,320
Gibbs	2,700
Allen-Moore	2,500-3,000
PPG-DeNora GLANOR V type 1144	2,280-2,580
Diamond D-3	2,720
LOW	2,280
AVERAGE	2,600
HIGH	3,000

TABLE III-19. COMPARISON OF DIAPHRAGM CELLS

Licensors	Hooker		Diamond Shamrock		ICI-Solvay		De Nora-PPG
Type	H4	H4	DS 85	MDC 55	DBT 26	DBT 43	Glanor V 1144
Description	Individual Rectangular cell units		Individual Rectangular cell units		Individual Rectangular cell units		Bipolar cells forming a filter press type electrolyser
	Standard asbestos diaphragms	Happ diaphragms narrow brine gap	Standard asbestos diaphragms	Modified asbestos diaphragms	Asbestos diaphragms		Deposited asbestos diaphragms
	Box type DSA	Box type DSA	Box type DSA	Expandable DSA	Titanium anodes		DSA
Operating current range (kA)	100-150		100-150		65-80	100-130	55-80
DC power usage at C.D. 2 kA/m per tonne of chlorine (kWh)	2860	2635	2860	2580	2625		2750
			(3070 at C.D. 2.4)	(2740 at C.D. 2.4)	(2790 at C.D. 2.4)	(2750 at C.D. 2.3)	
Current efficiency (5)	96-97.5						
Chlorine production per cell per day (tonne)	3.1-4.6		3.06-4.59		2.0-2.5	3.08-4.0	18-27 (For 11 cell units)
Date at which information provided	1975	May 1976	January 1976		January 1976		May 1976

Source: Burrows, M.G.T. "The Role and Development of Diaphragm Cells in the Chlorine Industry." Proceedings of a symposium held at the City University, London, England, June 16-17, 1976.

TABLE III-20. TYPICAL OPERATING CHARACTERISTICS
OF DIAPHRAGM CELLS

Rated cell capacity, ka	3-50
Cathode current density amp/sq cm	0.25
Average cell voltage	3.8
Current efficiency, percent	96
DC energy, kWh/ton	2,600
Diaphragm life, days	100
NaOH in cell liquor, percent	11
Temperature of catholyte, °F	200

TABLE III-21. MAJOR DEVELOPMENTS IN HOOKER CHLOR-ALKALI CELL TECHNOLOGY
1970-1980

Year	Developments	Result	Approximate Savings (% Reduction in Base Power Consumption)
1970-75	Most of Hooker's chlor-alkali cells converted to the use of dimensionally stable anodes.	Lower chlorine overvoltage called the H-4 cell.	---*
1972	Development of HAPP diaphragm	Thinner resin bonded diaphragms offer less electrical resistance	2-3%
1974	Closer anode-cathode spacing	Less internal resistance (IR) loss in the electrolyte	2-3%
1975	Improved electrical conductors, intercells, and joints	Lower IR loss in metal	1%
1976	Improved rectifier controls giving uniform operations	Lower billed cost of power	Varies
1977	Improved cell design taking advantage of optimized brine gap.	Increase in electrode areas, thus reducing current densities by 12 percent (LCD-low current density cell)	1-2%
			6-9%

*Power Consumption: 2,900 kWh per metric ton Cl₂

- (3) Use of coated cathode technology yielding another six to seven percent power savings. Its first commercial application was in 1979. The company is planning to use this technology in all its plants.
- (4) Planned construction in 1982 of a combined-cycle cogeneration plant at San Jacinto, Texas, that will supply 200 MW of electricity as well as process steam to serve the facility producing 1,400 tons per day of Cl_2 and NaOH each from diaphragm cells, and one billion pounds per year of vinyl chloride monomer.

Olin Corporation built a 1,000 ton-per-day plant in McIntosh, Alabama, in 1977. This plant uses 150,000 amp Hooker cells with resin-stabilized asbestos diaphragms and quadruple-effect evaporation of NaOH. A coal-fired boiler provides the steam. One compressor is used in place of many smaller ones, and heat exchangers are designed to tight temperature specifications. This plant raised the company's production capacity by 60 percent.

Kaiser Chemicals is currently converting all of its diaphragm cells to use the Diamond Shamrock expandable anode and plastic permeable asbestos diaphragm. Currently, a cogeneration system employing a heat recovery boiler and waste incinerator produces the power required for electricity and steam.

Vulcan Materials built a 675 ton-per-day caustic, 600 ton-per-day chlorine plant in Geismar, Louisiana, in 1976, which uses diaphragm cells. The steam requirement of 4,000 pounds per ton of caustic is a 30 percent improvement in efficiency over its Wichita, Kansas, plant and a 60 percent improvement over the one in Denver City, Texas. This is the first large-scale operation in the United States using Diamond Shamrock's largest cells (MDC-55). They use polymer-modified asbestos diaphragms and DSA, and operate with a smaller brine gap. The plant uses just one centrifugal compressor instead of the 14 used in the Wichita plant. Electrical power is bought at 260 kV, instead of 130 kV, to increase efficiency.

Uhde of West Germany has developed diaphragm cells using Hooker technology. These Hooker-Uhde (HU) cells have dimensionally stable box-type anodes and Holar asbestos diaphragms. One plant with 84 HU cells and a production capacity of 70,000 tons chlorine per year has been constructed.

In cooperation with PPG Industries, DeNora of Italy has helped to develop the Glanor electrolyzer diaphragm cell (25). PPG Industries has reduced its anodic overpotential to less than 0.1 volt through the use of titanium anodes. In the USSR, the chlorine industry has increased the production capacity of diaphragm cell units. Monopolar cells with loads up to 200 kA, and bipolar cells with loads up to 100 kA, are presently being developed (26).

3. Membrane Cells

a. Process Description. The membrane cell process is relatively new, and evolved from the mercury and diaphragm cell processes. The brine loop is similar to that of a conventional mercury cell, and the use of a separator is like that of a diaphragm cell. Membranes differ from diaphragms in that only positively charged ions (Na^+ and H_3O^+) can migrate through the membrane into the cathode section, and all negative ions are rejected due to a net negative charge inherent in the chemical makeup of the membrane. Saturated brine enters the anode section, is electrolyzed, forming chlorine gas and sodium ions, and is discharged from the same compartment. Water or dilute caustic is fed into the cathode compartment, electrolyzed, forming hydrogen gas and hydroxyl ions at the cathode. They combine with sodium ions coming through the membrane to form caustic soda. There is some leakage of hydroxyl ions and water into the anode section. This method permits direct production of caustic solutions of strengths up to 30 percent, and significantly reduces the amount of evaporation required when compared to conventional diaphragm cells (22). The caustic has a low residual brine concentration of about 50 ppm (17). Schematics of the three types of electrolytic cells are shown in Figure III-5.

Energy requirements for membrane cells consist of electrical power for electrolysis and steam for evaporation. Currently, electrical energy consumption is in the range of 2,800 to 3,300 kWh/ECU depending on the caustic concentration, which can range from 10 to 40 percent. Typical operating characteristics of membrane cells are not known for commercial-scale U.S. plants, but a reasonable estimate likely attainable in the next few years is shown in Table III-22. It should be noted that operating characteristics are highly dependent upon caustic concentration. Current efficiency is maximized at a caustic concentration of around 35 percent (29). Performance parameters for Japanese membrane cell technologies are shown in Table III-23.

(A)

(B)

(C)

Figure III-5. Chlorine Electrolysis Cells:
(a) Mercury Cell; (b) Ordinary Cell; (c) New Membrane Cell (6)

TABLE III-22. ESTIMATED OPERATING CHARACTERISTICS
OF MEMBRANE CELLS (29)

Cathode current density (amp/cm ²)	.3
Average cell voltage	4
Current efficiency, percent	90
DC energy, kWh/ton	3360
Membrane life, years	2
NaOH concentration, percent	35-40

b. Recent Membrane Cell Improvements for Energy/Power Reductions. The use of membrane cells in the United States has been limited to plant expansions, pilot-scale, and prototype plants. Very little of the chlorine production capacity of the United States is attributable to membrane cells. Only in the last year or two has there been a significant trend toward the increased construction of membrane cell plants.

The first commercial U.S. membrane cell plant was built and recently started by Fort Howard Paper in Muskogee, Oklahoma. The plant uses Hooker's MX membrane cells and duPont NAFION[®] membranes. Its initial capacity is 12.5 tons per day of chlorine, with an ultimate capacity of at least 25 tons per day.

Kaiser Chemicals is adding a trial line of membrane cells to its plant, with possible future expansion to plant size. Olin Corporation and Asahi Glass of Japan signed an agreement under which Asahi will supply membranes to Olin. Diamond Shamrock presently has six active projects underway using membrane technology: three in Canada, and one each in Japan, Sweden, and Brazil. It is expected that duPont will be the main supplier of membranes. In 1979 duPont completed a membrane production plant in Fayetteville, North Carolina, which will be capable of supplying the anticipated future requirements of membranes. In addition, to remain competitive with Japanese producers, duPont is working actively on modified NAFION[®] membranes which contain sulfonate and/or carboxylate groups. They hope to field a full line of chlor-alkali membranes to supply the market.

Foreign companies are a little farther along in membrane-cell plant production capacities. In Japan, Asahi Chemical's membrane chlor-alkali process is being operated commercially in the following four plants:

- (1) Asahi Chemical - Japan
- (2) Denki Kogaku - Japan

TABLE III-23. PERFORMANCE PARAMETERS
JAPANESE MEMBRANE CELL TECHNOLOGY

	Current Efficiency	Voltage	Current Density	Power Consumption	HCl Consumption	Caustic Concentration	Cell Temperature
Asahi Chemical Co.	93.4-94.8	3.81-3.90	4 KA/m ²	2698 to <u>KWH</u> 2776 MT NaOH	132 to <u>Kg</u> 146 Mt NaOH	40%	90°C
Asahi Glass Co.	92.0-95.5	3.80-3.87	2 KA/m ²	2667 to <u>KWH</u> 2781 MT NaOH	None	38.5 - 40.8%	85-90°C
Tokuyama Soda	94	3.50	2 KA/m ²	<u>2495 KWH</u> MT NaOH	<u>40 Kg</u> MT NaOH	20%	85°C

	<u>NaCl Depletion</u>	<u>Cell Type</u>	<u>Size of Membrane</u>	<u>Source of Membrane</u>	<u>Source of Anode</u>
Asahi Chemical Co.	70%	Bi-Polar	1.2m x 2.4m	Self Supply	Self Supply
Asahi Glass Co.	46 - 56%	Monopolar	1m x 2m	Self Produced	Purchase
Tokuyama Soda Co.	40 - 50%	Bi-Polar	270 dm ²	Self Supply	Purchase

Source: Woodard, K.E., Jr., and E.J. Rudd. Report of the Electrolytic Industries for the Year 1979, May 14, 1980, sponsored by the Industrial Electrolytic Division of the Electrochemical Society.

(3) St. Anne - Nackawic Pulp and Paper - Canada

(4) Saskatoon Chemicals, Ltd. - Canada.

The other Japanese chlor-alkali company involved in membrane cell technology is Asahi Glass Company, Ltd. This firm has developed membrane cells and the "Flemion" membrane. This is a permselective (selective permeability) ion exchange membrane made of a perfluoropolymer synthesized by a unique process from basic fluorochemicals. Several types of Flemion are made to meet different electrolytic conditions. The membrane cell developed by Asahi Glass is a monopolar, filter-press type of electrolyzer to optimize use of the Flemion membrane. This design lowers voltage requirements and allows variability of the current capacity for maximum efficiency. Asahi Glass operates a commercial chlor-alkali plant using this technology and the Flemion membrane in Osaka, Japan. Asahi Glass is also participating in a joint effort with PPG Industries to develop a membrane electrolyzer.

In Canada, there are three chlor-alkali plants operating with membrane cells. Two of these use Asahi Chemicals technology. Prince Albert Pulp and Paper Company started up a \$10 million plant at Saskatoon, Saskatchewan, called Saskatoon Chemicals, Ltd. The energy consumption of this 85 ton-per-day plant is about 20 percent less per ton than for any comparable plant. St. Anne-Nackawic Pulp and Paper Company started a 30 ton-per-day unit in Nackawic, New Brunswick, in 1979. Both of these plants use the Asahi Chemicals perfluorocarboxylic acid membrane and cell technology. The third chlor-alkali company using membrane cells is Reed Paper, which operates a 40 metric ton-per-day commercial chlorine plant in Ontario using Hooker membrane cells with NAFION[®] membranes.

Uhde of West Germany has developed a membrane cell based on Hooker technology. Uhde has developed a monopolar cell consisting of cathode frames of steel, anode frames of titanium, and a membrane frame. Uddeholm of Sweden started up a 60 metric ton-per-day commercial chlorine plant in 1978 at Karlstad using Diamond Shamrock bipolar membrane cells. In 1979, Veracruz Cellulose of Brazil started up a chlorine plant in Victoria using Diamond Shamrock membrane cells, which produces 35 metric tons per day. Capacity will eventually be boosted to 105 TPD of chlorine. Table III-24 contains a list of membrane cell plants for each major chlor-alkali producer using membrane technology.

TABLE III-24. MEMBRANE CELL PLANTS

I. Asahi Chemical Company Technology		
1.	Asahi Chemical Company Nobeoka, Japan 1976	80,000 MT/yr
2.	Prince Albert Pulp Company 1978 Saskatoon, Sask, Canada	30,000 MT/yr
3.	St. Anne-Nackawic Pulp & Paper 1979 Nackawic, New Brunswick	10,000 MT/yr
4.	Denki Kagaku Company 1978 Ohmi, Japan	60,000 MT/yr
5.	Akzo Zout Chemie Netherland BV 1980 Hengelo	280,000 MT/yr
6.	N.Z. Forest Product Ltd. New Zealand	100,000 T/yr NaOH
II. Hooker & Uhde Technology		
1.	Reed Paper 1975 Dryden, Ontario	13,000 MT/yr
2.	Ft. Howard Pulp & Paper 1980 Ft. Howard, Arkansas to be expanded	4,500 MT/yr 9,000
3.	Tofte Cellulose Fabrikk 1980 (Hurum) Norway	16,500 MT/yr
III. Diamond Shamrock Technology		
1.	Muscle Shoals 1975	3,000 T/yr
2.	Uddeholms AB 1978 Skoghall, Sweden	20,000 T/yr
3.	Aracruz Cellulose 1980 Victoria, Brazil to be expanded	13,000 T/yr 38,000 T/yr
4.	Nigerian National Paper	8,000 MT/yr
5.	Paek Kwang South Korea	9,000 MT/yr

TABLE III-24. (CONTINUED)

III. Diamond Shamrock Technology (Continued)		
6.	Korea Potassium South Korea	12,000 MT/yr KOH
IV. Ionics & Celleco Technology		
1.	Elkem Spigeverk 1980 Bremanger, Norway	10,000 T/yr
2.	ROT Chimica Monterey Mexico	72 MT/Day KOH 2,600 MT/yr
V. Asahi Glass Company Technology		
1.	Asahi Glass Company 1978 Kansai, Japan	10,000 T/yr
2.	P.N. Soda Waru Indonesia	undisclosed
3.	Paper Industries Corp. of Phillippines	undisclosed
4.	Uhde GmbH West Germany	3,000 T/yr
5.	Nippon Carbide Industries, Inc. Japan	1,450 T/yr
VI. Tokuyama Soda Company Technology		
1.	Tokuyama Soda 1977 Yamaguchi, Japan	10,000 T/yr
VII. Allied Chemical Corp.		
1.	Allied Chemical Syracuse Pilot Plant 1976	2,000 T/yr

Source: Woodard, K.E., Jr., and E.J. Rudd. Report of the Electrolytic Industries for the Year 1979, May 14, 1980, sponsored by the Industrial Electrolytic Division of the Electrochemical Society.

4. Other Processes

Besides the three predominant methods of chlorine production, 20 other fundamental processes or variations of existing processes have been identified. Nineteen of these processes, listed in Table III-25, are described in a study by Versar, Inc., under contract to Argonne National Laboratory (22). The objective of the study was to identify methods of improving energy efficiency in chlorine production. Since each basic process is described and technically evaluated in the Versar report, they will not be repeated here. The most promising processes in terms of engineering and economic viability and energy efficiency were determined to be (22):

- (a) Membrane process (with and without catalytic electrodes) previously described
- (b) Kel-Chlor
- (c) Mobay (direct electrolysis of HCl)
- (d) The Shell process (catalytic oxidation of HCl)
- (e) Oxidation of ammonium chloride.

The Kel-Chlor process is a nonelectrolytic process involving the oxidation of hydrogen chloride using an active homogeneous catalyst with a strong dehydrating agent. The Mobay process involves the electrolysis of waste hydrogen chloride using direct current. The Shell process is also nonelectrolytic and involves the catalytic oxidation of hydrogen chloride in the presence of a cupric chloride catalyst and air or pure oxygen. The oxidation of ammonium chloride to produce chlorine can be done by either of two similar processes. They both use ammonium chloride, oxygen, and nitrogen dioxide. One operates at ambient temperatures, producing chlorine and ammonium nitrate, and the other operates at higher temperatures, consuming more nitrogen dioxide, and producing chlorine and nitric acid.

The last process is a solid polymer electrolyzer. The Solid Polymer Electrolyte (SPE) brine electrolyte is a type of membrane cell with the additional feature of electrocatalyst support provided by the membrane. Developed by General Electric Company as part of their aerospace fuel cell technology, the SPE cell consists of a membrane cell with a proprietary fluorocarbon-bonded electrocatalyst system permanently bonded to the membrane (30). The use of a solid polymer electrolyte between the current collectors and the membrane eliminates the gap between cathode and the membrane, resulting in a much lower resistance than in other membrane cells. There is an added potential for lower resistance

TABLE III-25. BASIC CHLORINE PRODUCTION PROCESSES

β -Alumina Membrane Cell (E)*
Downs Cell (E)
Catalytic Oxidation of HCl Using Metal Chloride Catalysts (N-E)**
Catalytic Oxidation of HCl Using Rare Earth Catalyst (N-E)
Kel-Chlor (N-E)
Catalytic Electrolysis of HCl (E)
Direct Electrolysis of HCl (E)
Oxidation of FeCl_3 - Salt Complex (N-E)
Oxidation of Ammonium Chloride (N-E)
Catalytic Oxidation of Ammonium Chloride (N-E)
Conversion of Salt Using Sulfur Oxides (N-E)
Conversion of HCl Using Sulfur Oxides (N-E)
Conversion of HCl Using Hydrogen Peroxide (N-E)
Nitrification of Potassium Chloride (N-E)
Nitrification of Salt (N-E)
Oxidation of Salt on Clay Media (N-E)
Oxidation of Salt Using Silica Compounds (N-E)
Electrolytic Conversion of Magnesium Chloride (E)
High Temperature Conversion of Salt Plasma (N-E)

*(E) - Electrolytic Process
**(N-E) - Non-Electrolytic Process

Source (21)

through the membrane caused by more uniform current distribution. The net result is a lower operating voltage for the SPE cell. Table III-26 illustrates voltage losses for each cell component for both the SPE cell and a typical membrane cell, both using the Nafion 315 membrane and operating at 300 ASF and 80 to 90°C. Due to voltage savings in the area of 0.5 to 0.8V, SPE cell power consumption using a Nafion membrane is 2,050 kWh/metric ton NaOH (30). Current research on the SPE cell involves the use of oxygen cathodes to further reduce cell voltage.

TABLE III-26. VOLTAGE LOSSES IN TYPICAL
NAFION 315 BRINE ELECTROLYZERS*

	SPE Cell	Typical Membrane Cell
Decomposition Potential	2.2	2.2
IR Drop Through Electrode/ Current Collector	<0.1	<0.1
IR Drop Through Electrocatalyst	0.1-0.3	-
IR Drop Through Membrane	0.5	0.5
IR Drop Through Electrolyte	0.0	0.6-0.8
Cathode Overpotential	<0.1	0.2-0.4
Anode Overpotential	~0.1	0.1
Cell Voltage	3.1-3.4	3.8-4.1

*300 ASF, 80-90°C

Source: Coker, T.G. SPE Brine Electrolyzers. General Electric Co., U.S.A. In Proceedings of the Oronzio DeNora Symposium, Chloride Technology, Venice, May 15-18, 1979.

E. Current Research and Development Efforts

Most major U.S. and foreign chlor-alkali companies are conducting research and development on improving electrolytic cell performance and reducing energy consumption of the cells. The U.S. Department of Energy has assisted research programs in these areas. One such program, conducted by Diamond Shamrock and Case Western Reserve University, concerns the development of an oxygen depolarized cathode to replace the currently used hydrogen-producing cathodes in membrane and diaphragm cells. It is anticipated that a cell voltage savings of approximately one volt (or 28 percent) could be realized through the use of these cathodes (31). The cell reaction for the oxygen depolarized cathode is:

The usual cell reaction for currently used cathodes is:

The polarization of the oxygen cathode operating on air is about 0.2V greater than that of the hydrogen producing reaction, which results in the expected one volt savings.

Due to the higher purity caustic, membrane cells appear to be particularly appropriate for air cathodes, since the problem of catalyst poisoning is reduced. Researchers do not expect commercialization of this cathode for at least another five years. Oxygen cathodes capable of withstanding the extreme conditions in diaphragm cells have not been developed. Table III-27 contains cell voltage estimations for a membrane cell using both a hydrogen cathode and an air cathode (31).

The total energy saved will be less than 28 percent due to the absence of hydrogen, which can be, and often is, used as a fuel. Taking this into account together with the present efficiencies of coal-fired electric generating plants and the ancillary power requirements for air processing, the total energy saving is projected to be approximately 16 percent (31).

The successful commercialization of oxygen cathodes depends on its operating life, failure mode statistics, and cost. The high current density ($\sim 300 \text{ mA/cm}^2$) required because of high membrane cost presently has a negative impact on cathode life, particularly when operating on air rather than pure oxygen. Although specific performance data are not available, it is known that oxygen cathodes do not presently meet their performance goals. These goals are:

- (a) Minimum of one-year life with very low failure statistics for shorter times
- (b) Electrode cost not to exceed \$50 per kW-year of electric energy saved or \$15 per ft^2 for an operating life of one year.

Table III-28 shows the performance target for oxygen cathodes for use in membrane cells (31). In conjunction with this study, research is being conducted on platinum catalysts, and other metals to replace platinum, for use with high-performance oxygen cathodes.

TABLE III-27. CELL VOLTAGES ESTIMATED FOR MEMBRANE TYPE

Chlor-Alkali Cells [300 mA/cm^2 at 85°C With
15 Percent NaCl Anolyte and 30 Percent NaOH
Catholyte With H_2 and O_2 (Air Cathodes)]

	H_2 Cathode	Air Cathode ^d
Thermodynamic potential	2.25V	1.08V
Voltage losses ^a		
anode polarization	0.1	0.1
anolyte ohmic loss	0.2	0.2
membrane	0.5	0.5
catholyte ohmic loss	0.3	0.2 ^b
cathode polarization	0.3(0.1) ^c	0.4 ^d
Total voltage losses	1.4(1.2) ^c V	1.4V
Terminal Voltage	3.7(3.5) ^c V	2.5V

^aIncludes all losses within cells

^bAssumes no bubble field in catholyte and somewhat thinner membrane-cathode gap

^cParentheses numbers based on use of low H_2 overpotential catalyst such as Raney nickel

^dAssumes air at 1 atm.

TABLE III-28. PERFORMANCE TARGET FOR OXYGEN CATHODES
FOR MEMBRANE CELLS

Current density:	~300 mA/cm ²
O ₂ source:	air, CO ₂ free
Electrolyte:	≥30% NaOH (membrane cell grade)
Operating potential:	≥0.80V vs. RHE
Temperature:	~85°C
Life:	≥10,000 hours

F. Comparative Energy Requirements for Cell Types

The energy requirements for each cell type will vary according to many parameters, including cell design, manufacture, caustic concentration, current density, and operating voltage. Table III-29 contains energy usage values of three major chlor-alkali producers for each of the three cell types, mercury, diaphragm, and membrane. From this table and information presented in previous sections, average electrical and steam requirements for 1980 commercial mercury and diaphragm cells were determined. Incorporating recent improvements, diaphragm cells will use an average of 2,500 kWh/ECU and 4,500 lb steam per ton of caustic. Mercury cells will use about 3,200 kWh/ECU and very little or no steam. Figure III-6 shows the total energy requirement per ECU of diaphragm, membrane, and mercury cells. Total energy is the sum of electrical energy and the thermal energy equivalent of steam used to concentrate the caustic soda.

In comparing the performance of each cell type, an important aspect to be considered is the potential for further improvement in energy reduction. Table III-30 contains a summary of U.S. research and development efforts and their potential for reducing energy consumption in cell operation (where available). In addition, the expected time period for implementation is provided where known. It appears that very little, if any, research and development work is being done in the area of mercury cells. No information was available on specific work being done by any company in that area.

From the data presented in Table III-30, projections were made for reductions in cell power consumption. By

TABLE III-29. ENERGY REQUIREMENTS FOR
CHLOR-ALKALI INDUSTRY

<u>Olin Corporation</u>		
<u>Mercury</u>	<u>Diaphragm</u>	<u>Membrane</u>
50% caustic	11-12% caustic	35% caustic
3,200 kWh/ECU	2,400 kWh/ECU	2,400 kWh/ECU (projection)
Very little steam	6,000 lb steam/ton of caustic	1,000 lb steam/ton of caustic
<u>Hooker Chemicals</u>		
	<u>Diaphragm</u>	<u>Membrane</u>
	2,500 kWh/ECU	2,800 kWh/ECU
	4,500 lb steam/ton of caustic	
<u>Diamond Shamrock</u>		
<u>Mercury</u>	<u>Diaphragm</u>	<u>Membrane</u>
3,500 kWh/ECU	2,600 kWh/ECU	3,300 kWh/ECU
	4,000 lb steam/ton of caustic	1,700 lb steam

SOURCE: Personal communication with industry representatives.

* Spread reflects varying ages of plants

□ Electrical energy requirement; curve represents steam required for concentration of caustic to desired level.

Figure III-6. Energy Consumption in Different Types of Chlorine Cells
Current Technology

TABLE III-30. SUMMARY OF U.S. R&D TO REDUCE ENERGY CONSUMPTION
IN CELL OPERATION

R&D EFFORT	COMPANY	CELL TYPE		CELL VOLTAGE REDUCTION	POWER REDUCTION	COMMERCIALIZATION TIME	REMARKS
		MEMBRANE	DIAPHRAGM				
Cell Design Improvements	Diamond Shamrock	X	X	N.A.	--	N.A.	Use of high cell pressure in diaphragm cells
	Hooker	X	X	Reduce current directly by 25% to 1.77 kA/m ²	--	N.A.	LCD diaphragm cell
	PPG	X		N.A.	--	N.A.	Bipolar cell with Asahi Glass of Japan
	Olin	X		N.A.	--	N.A.	
	Allied	X		N.A.	--	N.A.	Uses NAFION membrane
Hybrid Cell	Hooker	X	X	N.A.	--	>5 years	Combination of diaphragm and membrane cells
Cathodes:							
Oxygen	Diamond Shamrock	X	X	1V	28%	>5 years	No hydrogen produced - total energy saved is 16%, considering power plant efficiency
	Hooker	X	X	N.A.	--	N.A.	
Metal Coated	Diamond Shamrock		X	.1 to .2V	6%	1 year	Beginning commercialization
Steel Mesh w/ Nickel Alloy	Hooker	X	X	Reduces over- voltage by 50-60%	4-5%	1 year	
Steel Mesh w/ Nickel-Aluminum Alloy	Hooker	X	X	Reduces over- voltage by 75-80%	5-6%	N.A.	
Hydrogen Over- voltage	Hooker	X	X	N.A.	--	>5 years	
Catalytic	Hooker	X	X	N.A.	--	2-3 years	
Cobalt-Tungsten Coated Steel	PPG		X	.17 to .25V	7%	N.A.	
Proprietary Coatings	Olin	X	X	--	5%	N.A.	
Catalytically Active Porous Raney Nickel Coated	duPont		X	--	6-8%	1 year	Full size prototypes now being tested
Anodes:							
Hydrogen Evolving	Diamond Shamrock	X		N.A.	--	N.A.	
CO-Zn-Zr Oxide Coating on Titanium	Dow		X	--	--	N.A.	Projects a useful life of about 6 years
Rhenium or Ruthenium Oxide Coating	Olin	X	X	N.A.	--	N.A.	

TABLE III-30. (CONTINUED)

R&D EFFORT	COMPANY	MEMBRANE	CELL TYPE DIAPHRAGM	CELL VOLTAGE REDUCTION	POWER REDUCTION	COMMERCIALIZATION TIME	REMARKS
Anodes:							
Titanium- Ruthenium Coating	Allied	X		N.A.	--	N.A.	Prototype cells being tested
Flexible Conversion	Hooker	X	X	N.A.	--	N.A.	
Separator	Diamond Shamrock	X	X	N.A.	--	N.A.	Non-permeable membrane/plastic reinforced diaphragm
	duPont	X		--	--	Present	NAFION [®] membrane - full-scale production plant
	Hooker		X	--	7%	1 year	Microporous separator
Brine Gap	Diamond Shamrock		X	N.A.	--	N.A.	
	Hooker		X	--	1%	N.A.	50% reduction in gap
N.A. - Not available							

1985, it was assumed that coated metal cathodes would reduce diaphragm cell power consumption by about six percent, and improved separator materials would reduce power consumption another seven percent, for a total of 13 percent electrical power reductions. Thus, electrical power required per ton of chlorine for diaphragm cells in 1985 will be about 2,180 kWh.

Membrane cells consume an average of 2,800 kWh/ton of chlorine. By the year 2000, when membrane cells are contributing a large percentage of the U.S. chlorine production, oxygen cathodes will have been commercialized and in wide use. Since oxygen cathodes can be used only in membrane cells, a 28 percent reduction in electric power requirements will be achieved for membrane cells. However, the 56 pounds of hydrogen produced per ECU as a by-product of chlor-alkali electrolysis with conventional cathodes are not produced when the oxygen electrode is used. Taking into consideration the high heating value of hydrogen (61,084 Btu/lb), this means a loss of 3.4 million Btu of thermal energy per ECU. An additional one percent power reduction will be achieved by diaphragm cells through further brine gap reductions. It is not anticipated that any significant further power reductions will be achieved for mercury cells. Thus, the projected electrical energy use in the year 2000 is 2,020 kWh/ton of chlorine for membrane cells, 2,160 kWh/ton of chlorine for diaphragm cells, and 3,200 kWh/ton of chlorine for mercury cells.

G. Economic Evaluation

1. Production Cost

The following analysis of production costs and return on investment is based on data provided by Diamond Shamrock Corporation for a newly built chlor-alkali plant with a rated capacity of 310,000 short tons of chlorine per year. A cost analysis is presented for both diaphragm and membrane cell processes. The estimates are based on the following assumptions:

- Plant operates 350 days per year
- Daily chlorine output is 848 tons
- Daily caustic soda output is 943 tons
- Membrane replaced every 24 months
- Diaphragm replaced every 12 months

- Membrane cell plant investment:
\$137,200,000
- Diaphragm cell plant investment:
\$138,200,000
- 12-year plant life
- Annual plant overhead: 5 percent of total plant investment
- Annual maintenance and repair: 5 percent of total plant investment
- Electricity cost: \$.035 kWh
- Steam cost: \$3.30 per 1000 lbs.
- Operator labor rate: \$12/hr.
- Supervision and indirect payroll:
30 percent of operating labor + 5 supervisors
at \$32,000/year

a. Production Cost Analysis for the Membrane Cell

(Dollars per ECU)

Raw materials	\$36.20
Electricity (2,936 kWh)	\$102.70
Steam (1,800 lbs)	\$ 5.50
Labor, supervision, and repair	\$ 39.30
Plant overhead	\$ 23.10
Capital recovery*	<u>\$ 73.00</u>
TOTAL	\$279.80

*Capital Recovery = Capital Recovery factor x plant investment per annual ton of capacity. The capital recovery factor for a 12-year plant life (12-year payback period), using 12.5 percent before-tax cost of capital, is 16.5 percent.

b. Production Cost Analysis for the Diaphragm Cell Plant

(Dollars per ECU)

Raw materials	\$29.20
Electricity (2,718 kWh)	\$95.10
Steam (4,500 lbs)	\$13.60
Labor, supervision, and repair	\$32.50
Plant overhead	\$23.10
Capital recovery	<u>\$73.00</u>
TOTAL	\$266.50

Economies of scale in production favor larger plants. The total plant investment cost per ton of annual production tends to decrease with increasing capacity up to approximately 300,000 tons of chlorine per year. (Membrane cells appear to be more economical than diaphragm cells in smaller plants.) Whereas the cost for a 300,000 ton/year plant is approximately \$445/annual ton of capacity, the cost for an 80,000 ton/year plant is over \$1,300/annual ton of capacity. The high cost of transporting chlorine and caustic soda to customers tends to limit the maximum economic plant size. The average freight charge for these two products comprises 18 percent of the total sales revenue.

2. Trends

Increasing power costs and capital costs will continue to have a major impact on chlor-alkali production economics. Between 1972 and 1977, the average cost of electricity used by the industry increased by 140 percent. Annual increases between 1980 and 1985 are expected to exceed 14 percent. Capital costs increased by 170 percent between 1972 and 1980, and are expected to increase at an annual rate of 7 percent through at least 1985.

3. Type of Plant

At present, 75 percent of all chlor-alkali produced in the United States is processed by diaphragm cells, 20 percent by mercury cells, and 5 percent by other processes. Membrane cells are not yet used to a significant extent in the United States.

Although most of the major chlor-alkali producers using mercury cell plants have no plans for shutting down operations or converting plants to diaphragm or membrane cells, it is anticipated that no new plants or plant expansions will have mercury cells. In addition, industry representatives indicate that by 1985 about 500,000 tons of chlorine capacity now using mercury cells will be converted to diaphragm or membrane cells. It is not anticipated that any significant increase in chlorine production by membrane cell plants will occur by 1985. Therefore, diaphragm cell chlorine production will increase its share of total U.S. production to about 82 percent by 1985, assuming a constant 5 percent share is attributed to other production processes. Chlorine production by mercury cell plants will drop to about 13 percent of the U.S. total in 1985.

Firm projections on the use of membrane cells by the year 2000 are presently unavailable due to the relative newness of membrane cell technology, and the uncertain economics of its use in the United States. The United States is lagging behind many of the world's chlorine-producing nations in the use of this new technology. One reason for this is that a higher purity of brine is required for membrane cells than for diaphragm cells. European producers have already installed high-purity brine feed systems because they were needed for mercury cells. Converting to membrane cells is therefore less costly for these producers than for companies in the United States, which have relied primarily on diaphragm cells. However, membrane cells have certain important advantages over diaphragm cells that will promote their use in the United States. Membrane cell chlor-alkali plants are more suitable than diaphragm plants for remote locations; they are preferred in situations of variable power supply and where a high-purity caustic soda is required. Membrane cells are particularly effective in applications where a 30 percent caustic soda concentration is required. No evaporation system would be needed since the caustic soda output of a membrane plant is already 30 percent.

It is the general feeling that membrane cells will begin to establish a foothold in the chlorine industry in the latter half of the 1980s. Opinion among industry spokesmen varies as to the extent of projected membrane cell use. One industry representative suggests that membrane cells will probably become the new standard for chlorine plants in the 1980s (36). Another feels that "over the next 10 years (from 1979) membrane cell technology will account for a minimum of 20 percent, and perhaps as high as 50 percent of the new chlor-alkali capacity added around the world" (3). An even more optimistic spokesman feels that the membrane cell will totally replace the diaphragm and mercury cells by the end of the 1980s (38). The most realistic projection appears to be

that the majority of new plants will continue to use diaphragm cells up to 1985 or 1986, at which time membrane cells will be virtually the only cells installed in new plants and expansions (14). Assuming that 90 percent of the new plants (built from 1985 to 2000) are equipped with membrane cells by the year 2000, membrane cell plants will be producing 36 percent of the United States' total output. This amounts to approximately 9×10^6 tons of chlorine per year by the year 2000.

Mercury cell plant production should decrease slightly as more cells are converted to diaphragm and membrane cells. Based on an average annual historical decline rate of 3.0 percent for mercury cell use, by the year 2000 mercury cell plant production of chlorine should be about 5 percent of total U.S. production, or about 1.3×10^6 tons of chlorine. Chlorine production with diaphragm cells should drop to about 54 percent, while actual production will probably increase slightly to about 13.5 tons of chlorine in 2000. Other production processes will most likely maintain their 5 percent share of the market, producing 1.2×10^6 tons of chlorine in 2000. Table III-31 contains a summary of chlorine production by cell type for 1980, 1985, and 2000.

Total electrical energy consumption figures were generated for 1985 and 2000 on the basis of the energy consumption projections generated for each cell type in Section IV-E. These are listed in Table III-32 along with projected 1980 data. The total U.S. electrical energy consumption savings achieved by the chlor-alkali industry through the implementation of cell improvements are calculated. Assuming that no improvements were made, the projected 3.5 percent industry growth rate, applied to the 1980 energy consumption figure of 3.1×10^{10} kWh, would yield an electrical consumption figure of 3.7×10^{10} kWh in 1985 and 6.2×10^{10} kWh in the year 2000. Thus, projected electrical energy savings are about 16 percent for 1985 and 18 percent for the year 2000. Further reductions will be required by the chlor-alkali industry to meet the U.S. DOE goal of 30 percent energy reduction by the year 2000.

TABLE III-31. EXPECTED PRODUCTION OF CHLORINE TO
THE YEAR 2000

	Production (x 10 ⁶ tons)	Mercury (%)	Diaphragm (%)	Membrane (%)	Others (%)
1980	12.5	20	75	--	5
1985	15	13	82	--	5
2000	25	5	54	36	5

TABLE III-32. U.S. ELECTRICAL POWER CONSUMPTION
FOR CHLOR-ALKALI INDUSTRY

	(x 10 ¹⁰ kWh)			
Year	Mercury	Diaphragm	Membrane	Total
1980	.8	2.3	--	3.1
1985	.6	2.7	--	3.3
2000	.4	2.9	1.8	5.1

4. Market Trends

In 1979, 12.3 million tons of chlorine were produced in the United States. While this was a 10 percent increase over 1978 production, chlorine demand in 1980 is expected to grow at only 4 percent per annum (39). Since the total plant capacity of the U.S. chlor-alkali industry was 14.6 million tons at the end of 1979, the industry-wide plant utilization rate was 84 percent. At present, 738,000 tons/year of new capacity is under construction. No new capacity has been announced for beyond 1981 (40).

Since 1973, chlorine production has grown at about half the rate of total U.S. industrial output (41). This slow growth rate is attributed to several factors: (42)

- New processes have been developed that avoid the use of chlorine in making chemicals such as methylene diisocyanate and nylon. The new processes are preferred because they are less polluting.

- Use of chlorinated solvents, such as trichloroethylene, has declined due to environmental concern and the difficulty of disposal. Non-chlorinated solvents are being used in their place.
- Use of fluorocarbon in aerosols has diminished due to concern over its effect on ozone in the upper atmosphere.
- Demand for ethylene dichloride, used in polyvinylchlorides (PVC), is expected to decline as PVC exports decrease. PVC production is now increasing in countries that have previously bought PVC from American producers.

There is no foreign trade in chlorine due to the difficulty of shipping it.

Caustic soda production by U.S. chlor-alkali plants was 12.4 million tons in 1979, exceeding 1978 production by nearly 15 percent. The demand for caustic soda is expected to increase about 5 percent in 1980. Approximately 17 percent of U.S. caustic soda production was exported in 1979. This export trade could be weakened by the construction of chlor-alkali plants in developing countries that have been markets for U.S.-produced caustic soda (43).

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IXI-62

IV. APPROACHES TO ACCELERATED RESEARCH AND DEVELOPMENT IN THE ELECTROLYTIC INDUSTRIES

A. Introduction

This section examines factors which hinder accelerated research and development (R&D) by the electrolytic industries and makes suggestions for government actions to promote R&D directed toward reducing energy requirements in these industries.

Research and development is viewed as an investment by corporations; therefore, the barriers to R&D are similar to the barriers to any corporate investment. The barriers examined in Part B of this section include technical and market uncertainty, restrictions on data and patent rights, and capital availability.

Possible federal government actions for overcoming these barriers and for promoting R&D are identified and discussed. Certain types of relevant government action, including tax incentives, loan guarantees, and trust funds are mentioned but not treated in detail because they are beyond the scope of actions that can be implemented by the study's sponsors. The types of action that are within the scope of this study, which are discussed in more detail, include forms of federal assistance that are targeted on specific R&D objectives. They consist of federal grants, cost-sharing, sponsorship of national laboratory research, and information transfer programs.

B. Barriers to Accelerated R&D

Several studies have indicated that the private sector treats decisions to undertake R&D as investment decisions (1,2,3,4,5). Therefore, corporate decisions to undertake R&D will be influenced by the same basic forces that influence decisions for other investment projects. These forces can be broadly classified into two categories: (1) the relative attractiveness of the R&D investment in comparison to other investment opportunities, and (2) the cost and availability of funds for investment.

Within each of these categories there will be several factors that can act as barriers to R&D. Some of these can be alleviated by federal assistance that is directly targeted on specific R&D objectives. Others appear to require less direct fiscal measures that are targeted on R&D in general. This analysis will be concerned with the former type of

barriers. The latter, those requiring broader approaches, will be reviewed but not discussed in detail.

1. R&D as an Investment

The relative attractiveness of any R&D project as a investment is determined by its projected after-tax return on investment (ROI) and its risk.

The factors that influence return on investment are such that their modification will usually require changes in government fiscal policy which can only be brought about by legislative or regulatory action. Some of these factors are identified below; however, suggestions for modifying them as an approach to stimulating R&D in the aluminum and chlor-alkali industries are outside the scope of suggestions that this study will consider. Therefore, with one exception, they are not given detailed attention. The exception involves rights in technical data and patents, a factor that is relevant to the types of suggestions that this study can consider.

The factors that influence the risk accepted by a corporation in undertaking R&D vary; some are amenable to influence by direct actions within the range of those considered by this study. These barriers are discussed in more detail.

a. Return on Investment (ROI). For the purpose of this study, the research "product" is a more energy-efficient process for producing aluminum or chlorine. The return on such research investment derives from increasing or maintaining a market share for the existing refined products through price maintenance made possible by the reduction of energy-related production costs.*

In general, the factors which will influence the after-tax ROI are:

- (1) Demand for the product produced by the process
- (2) Price of the product produced by the process
- (3) Royalties or fees from licensing of the process
- (4) Corporate tax rate

**The marketable products, e.g., aluminum and chlorine, are not the focus of the R&D investments examined here. The concern is with improving the profitability of existing products through research that reduces the costs of producing them.*

(5) Projected production operating costs excluding depreciation

(6) Depreciation schedule.

Mechanisms which affect these factors so as to result in a low projected ROI for a research product will reduce the attractiveness of major R&D investment in that product (or process).

Numerous economic, financial, and institutional mechanisms have such an effect and therefore will act as barriers to accelerated investment in R&D. Some of these mechanisms are more amenable to government control than others. As noted above, however, legislation or regulatory action is generally required to implement such control, and therefore, with one exception, these barriers will not receive detailed consideration. Examples include:

(1) Corporate tax policy

(a) Corporate income tax rate

(b) Depreciation schedule

(2) Government regulation

(a) Health and safety regulation

(b) Environmental regulation

(c) Rights in technical data and patents.

(1) Corporate Tax Policy.

(a) Corporate Income Tax Rate. Taxation of corporate income directly affects ROI by reducing cash flow. Recent changes in the tax laws have ameliorated the effect of corporate taxation on cash flow; however, it remains as one barrier to more risky types of research investment.

(b) Depreciation Schedule. The rate at which depreciation may be taken on an investment in a new process affects the cash flow from that investment. Therefore, the depreciation schedule also affects the return on investment. Revising the depreciation schedule may be an incentive to greater investment in higher risk R&D.

(2) Government Regulation.

(a) Health and Safety Regulations. Health and safety regulations affect ROI by increasing both initial and operating costs. The impacts of these regulations have begun to be felt relatively recently. A recent study has indicated that since the early 1970s health, safety, and environmental regulations have had an effect on corporate managers' evaluation of investment options, including their investment in R&D (1).

(b) Environmental Regulation. The federal government has instituted environmental controls on pollutants for the same basic reasons that it established health and safety regulations: to raise the level of health protection for the populace above that provided by market forces alone. The result has been the promulgation of numerous regulations aimed at controlling air, water, and noise pollution. In the chlor-alkali industry, for example, EPA regulations limiting the amount of mercury that may be discharged have necessitated the purchase and installation of new filter systems and coolers to condense mercury vapor. Any evaluation of a research proposal aimed at improving the energy efficiency of mercury cells must consider the costs that will be required to maintain and operate the environmental control equipment.

(3) Rights in Technical Data and Patents. The attractiveness of investing in research lies in the hope of realizing a higher-than-average return on a new product or process. The higher ROI is made possible by the technical advantages that the research creates for the new product or process and, in the case of a process, by the royalties received from licenses to others to use it. The ability of the enterprise to sustain these advantages and earn royalties, thereby sustaining its higher ROI, will depend upon its ability to retain control of the technical data/knowledge upon which the advantages are based.

When this ability is impaired, the incentive to invest in R&D is seriously weakened. If the research is funded exclusively by private sources, control of the technical information is provided by patent rights and industrial security measures. Under such circumstances, rights-in-technical-data and patent issues are not a barrier to R&D. When the research is partially or wholly funded by the government, however, exclusive control of the resulting data and patents is forfeited. To the corporation interested in gaining a competitive advantage, this can be a barrier to the acceptance of

governmental assistance. If it acts as such, it will also be a barrier to the acceleration of research by government action.

A specific circumstance under which the potential loss of rights in technical data and patent rights may be a particularly serious barrier to the acceptance of government R&D assistance occurs when a proposed effort will require a major investment of private funds in addition to the government support. Many private investors will require a significant incentive to make such a commitment and are likely to consider exclusive patent and data rights to be a necessary part of that incentive (6).

Considerable controversy exists on the subjects of rights in technical data and patent rights where government R&D assistance is involved. The major argument supporting present policy (assigning such rights to the government) maintains that public funds should not be used to give a competitive advantage to a single private company. A major argument used against the policy holds that private enterprise can commercialize a new technology much faster -- and bring its benefits to the public sooner -- if it can retain the technical rights to it, thereby having an incentive to implement the technology and actively market it to others through licensing arrangements (7,8).

Present law gives the U.S. government unequivocal rights to the technical data and U.S. patents generated by research funded either in whole or in part by the government (see Section C below). The law does not require the government to exercise its rights, however, and some federal agencies have declined to do so.* Patent rights may be waived by the government in the contract negotiations establishing the assistance agreement between the government and researcher. DOE, however, has shown a preference for exercising these rights in the government's behalf (7).

b. Risk. R&D investments are by their very nature subject to a greater chance of failure than most other corporate investments. The payoff for those that succeed is often (but not always) large; unfortunately, relatively few succeed. The probability that an R&D investment will not be profitable is the risk that a corporation accepts in undertaking the research.

**When a federal agency elects not to exercise its rights, they inhere in the contractor and are not subject to challenge even through the Freedom of Information Act (Forsham, et al., v. Harris, U.S. Supreme Court Case No. 78-1118, 1980).*

Three types of risk affect the success of a research investment (1):

- (1) Market risk
- (2) Business or general economic risk
- (3) Technical risk.

For the purposes of stimulating R&D, the first two of these three types of risk are beyond the reach of government action of the type being considered here. The third type of risk, on the other hand, is subject to influence by direct government action and is, in fact, the explicit target of several forms of such action.* Brief mention will be made of the first two types of risk. Greater attention will be given to the third type of risk, technical risk.

(1) Market Risk. Uncertainties will always be associated with the economic projections for a new product. The accuracy of the projected return, especially in the case of more efficient processes, is dependent upon the accuracy of the projections of factor prices and the likelihood that a superior competing process will capture the market during the time period of the projections. The development of a technically feasible product or process requires time, and the longer the time taken in the development of the product, the greater the risk that the original projections will be erroneous.

(2) Business or General Economic Risk. General business and economic conditions can prevent a commercialized product or process from generating its expected sales. High interest rates, for example, may restrict the capital that is available to prospective buyers, slowing the rate of market penetration of the new product or process. Or a general economic downturn may cause purchasers to delay new commitments for several years. Such macro events will reduce the actual ROI realized.

(3) Technical Risk. Technical risk is the fundamental attribute of any R&D undertaking. Given the existing base of theoretical and technical knowledge, the scientific manpower available and budget resources,

**Unless otherwise indicated, "risk" and "investment risk," as used in this chapter, will refer to the collective risk resulting from the combined effects of the three types of risk listed. Generally, the magnitude of the collective risk will be greater than the risk imposed by any one of the types of component risk acting alone.*

it may not be possible to achieve the technical objectives within the defined time frame. The probability that the technical objectives will not be achieved is the undertaking's technical risk.

The magnitude of the technical risk is dependent upon many factors, several of which are amenable to government influence. The factors include:

- (a) The degree of inventiveness required
- (b) The time set for achieving the technical objectives
- (c) The quality of the scientific and technical manpower committed
- (d) The adequacy of the research facilities and equipment committed
- (e) The adequacy of the financial resources committed
- (f) The probability of continued support for the project throughout its planned duration, including political (corporate and government), and labor support (9).

These factors are interdependent. For example, at least three of them are partial functions of a fourth, the adequacy of the financial resources committed. The three are: the time set for achieving the technical objectives, the quality of the scientific and technical manpower committed, and the adequacy of the research facilities and equipment committed. To the extent that these can be influenced by the adequacy of financial resources, they can be influenced by the type of government financial assistance that lies within the scope of this study.

Another factor, the degree of inventiveness required, can also be influenced by government action. Highly speculative ideas are difficult to sell to investment decision makers. For such ideas, government-sponsored basic research, either by the national laboratories or through university grants, can be undertaken to reduce the level of inventiveness required. If successful, this level, at some point, will be low enough to make the risks of further development appear acceptable to private investors.

2. The Cost and Availability of Funds for Investment

Several economic studies of annual R&D expenditures by corporations have indicated that the level of these expenditures is significantly related to a corporation's level of retained earnings and internally generated cash flows (10,11,12,13). These studies generally attribute this relationship to the much greater uncertainty and longer development time associated with research. Corporate managers want to have a secure financial base for these investments. Research conducted for this report suggests that similar relationships exist for the aluminum and chlor-alkali industries.*

Mechanisms which reduce retained earnings, therefore, or discriminate against other forms of equity development also act to reduce the opportunities for accelerated R&D.** Numerous economic, financial, and institutional mechanisms have such an effect. All of the mechanisms that affect ROI that have been discussed also affect the availability of capital through their impact on retained earnings. Some of these, as has been discussed, are amenable to government action of the type considered by this report.

There are other mechanisms as well. For the most part, however, these remaining mechanisms are not amenable to government influence by the types of action that lie within the scope of this study. These barriers will be mentioned, but not discussed in detail. They involve, principally, debt financing for non-R&D projects, and corporate tax policy.

*Correlations (R^2) between total R&D expenditures and profit were found to be, for the aluminum industry, .71 ($\alpha=.14$), and for the chlor-alkali industry, .96 ($\alpha=.106$). The correlations are based on data taken from the 1977-1980 reports of R&D spending by major corporations compiled by Business Week from the companies' 10-K reports to the Securities and Exchange Commission (14,15,16,17).

**Capital for R&D investment can also be raised through equity sales; therefore, mechanisms which reduce the attractiveness of new stock offerings will also act as barriers to accelerated R&D. However, the financing of R&D through this form of equity development appears to be more common among very small firms than larger ones. Since the corporations that constitute the aluminum and chlor-alkali industries are relatively large, this method of increasing the capital available for R&D investment is considered less relevant for this study. Accordingly, it has not been examined. Debt financing is another method of raising capital. It is used relatively less in R&D financing -- probably because of the added risks involved -- and, therefore, also is not considered here.

Those aspects of corporate tax policy that were cited for their impact on ROI are also relevant for capital availability; they will not be reconsidered. The mechanisms mentioned here include:

- (1) Debt financing: high interest rates
- (2) Corporate tax policy: lack of tax incentives for R&D.

a. Debt Financing: High Interest Rates. High interest rates for corporate borrowing affect the availability of capital for R&D investment in two ways. First, high interest rates make the cost of financing R&D through loans very unattractive. However, this method of capitalizing research is seldom used by large companies. Second, and of greater relevance, high interest rates affect the capital available for research by forcing corporate managers to dip into retained earnings for non-research investments.

By forcing firms to finance non-research investments out of internally generated funds, high interest rates reduce the availability of this traditional source of financing for R&D. During periods of prolonged high interest rates, it may be difficult to motivate companies to invest in new research initiatives or to accelerate existing ones. Research that is fully funded by outside sources may be particularly attractive during such periods.

b. Corporate Tax Policy: Lack of Incentives for R&D. Corporate taxation policy contains several incentives that may be considered as stimulants to investment in general, but very few that are specifically directed to R&D investments. Of those that are directed to R&D, the foremost is, perhaps, that incentive which permits firms to fully deduct outlays for research and development activities in the year the expenditures are incurred (Section 174 of the IRS Code). Such immediate expensing of R&D expenditures is equivalent to granting instantaneous depreciation to this form of investment. The effect is to make more capital available for initiating and supporting R&D projects.

This provision applies only to a portion of the total R&D investment, however. It does not apply to expenditures for capital assets used in R&D nor to costs incurred by purchasing patents or processes used in R&D. Depreciation for such items is governed by the same guidelines that apply to other investments of the firm.

3. Summary

There are several barriers to accelerated private R&D which the government can influence directly through the types of assistance that are being considered by this study. These are:

a. Technical Risk. Government assistance can directly affect technical risk by making available some or all of the funds needed to create a productive research environment. Where a large degree of innovativeness is required to achieve a technical objective, the government can fully fund the preliminary basic research in order to reduce the magnitude of the creative leap that must be taken at later stages of R&D.

b. Capital Availability. Under certain conditions, R&D investments may not appear to be as attractive investments as non-R&D investments. Given a situation in which externally generated capital is not feasible and non-R&D investments are capturing the available internal capital, opportunities for full government funding may exist.

On the other hand, research assistance from public funds may, itself, create a barrier to accelerated R&D. If this assistance entails a loss of rights to technical data or patents, it may be declined by firms not wishing to give up a principal means of increasing their ROI through R&D. This will be a particular concern where a firm must put up a major portion of the R&D funds itself.

In the next section, the methods of governmental assistance covered by this study are identified and discussed.

C. Suggestions for Promoting R&D Through Federal Government Action

Governmental methods for stimulating R&D fall generally into three categories:

- (1) Privately financed R&D with government stimulus
- (2) Government-private cost sharing
- (3) Government-financed R&D.

Each method is designed to encourage R&D by transferring to the government some (or all) of the risk that industry would otherwise have to bear alone and/or by making available some of the capital that private industry would need to undertake the risk by itself.

1. Privately Financed R&D With Government Stimulus

The first of these categories involves federal action that is outside the scope of this study. Activities in this category stimulate R&D through financial and regulatory provisions that affect either the return on investment that a corporation can expect from its R&D investment or the capital that it has available for such investment. These provisions create an incentive -- or in some cases, a penalty -- which is designed to encourage private industry to undertake R&D at its own risk, i.e., to accept full responsibility for the R&D investment. Legislative authority usually is required for this type of activity. Typical provisions include accelerated depreciation schedules; adjustments to depreciation basis; revisions to health, safety, and environmental regulations; investment tax credits; and use of a federal R&D trust fund. As noted, this category of activity lies outside the scope of this study and will not be examined beyond noting that it exists as one set of options for government activity to stimulate R&D. The rest of this section will examine the two remaining categories: government-private cost sharing and government-financed R&D.

2. Suggestions to Stimulate R&D Through Cost Sharing

Cost-sharing arrangements between government and the private sector are familiar forms of stimulating research and development. Both basic research and demonstration projects are eligible, although cost-sharing arrangements appear to be better suited for projects that have reached the demonstration stage (18).

Cost-sharing arrangements have several advantages and disadvantages from the public point of view.* They can be tailored to specific industries and specific types of outcomes without necessarily constraining the proposers' creativity. Active government participation in the project is possible, leading to some control over the project and its outcome. Compared to the use of tax and regulatory incentives, the cost to the government is more predictable. If the arrangements include repayment terms, as some do, the nation is eventually reimbursed. Where high- or moderate-risk technical advances are considered to be in the public interest, this form of government-private risk-sharing arrangement may make possible research or demonstration outcomes that private industry alone would never achieve.

**The Department of Energy instrument for implementing cost-sharing arrangements is the Cooperative Agreement. Regulations pursuant to the use of Cooperative Agreements are in 10 CFR 600.200-290.*

On the other hand, cost-sharing arrangements may be considered discriminatory in that only a limited number are available and most firms in an industry will not receive the benefits that they offer (19). This disadvantage can be partially overcome, however, by offering all firms in an industry the opportunity to compete for the cost-sharing arrangements.

The cooperative agreement is applicable to low-risk, marginal advances as well as to high-risk, major advances. Its application to low-risk technical advances should have the effect only of accelerating the process since, presumably, low-risk advances would eventually be completed with private capital anyway.

From the point of view of industry, cost sharing is a method of reducing the overall risk associated with technically risky or prohibitively expensive projects. Cost sharing may make possible a high-payoff, but risky, project that otherwise would not receive serious consideration by corporate decision makers.

The participating firm may not claim a fee from the government for its share of the work in the project, no matter how large that share. This is considered a minor disadvantage of cooperative agreements, however. The major disadvantages to a firm in this method of stimulating R&D are the potential loss of proprietary rights in the technical data developed under the cost-sharing arrangement and the restrictions on new patents. Department of Energy regulations governing cooperative agreements require that the government have unlimited rights to data developed by the project (20). This usually means that such data, if it cannot be demonstrated that they were developed solely at private expense, can eventually become available to the firm's competitors through government sources. Since such data were developed, at least in part, at the risk of the firm, this may be seen as a serious disadvantage of cooperative agreements. The offsetting advantage for this drawback is the early lead the participating firm gains in experience with the new data.

Similar restrictions pertain to patents for discoveries made as a result of the project. The rights to any inventions developed under the project rest in the government (21). Inasmuch as the government's objective is usually commercialization, however, the government's waiver policy is liberal (7). Additionally, the participating firm retains a certain scope of licensing rights even without waivers.* For demon-

**The applicable patent rights and conditions are discussed in Department of Energy Procurement Regulations §9-9.1, especially 9-9.100, 9-9.107-3, 9-9.107-5, 9-9.109-6.*

stration projects where few new inventions are expected, this is not likely to be a significant barrier to industry acceptance of cooperative agreements.

3. Suggestions to Promote the Development of Energy-Efficient Processes Through Government-Financed R&D

Each of the two preceding categories utilized partial government financing to stimulate accelerated R&D. The third category covers government R&D assistance efforts in which the government provides 100 percent of the financing or other form of assistance. In this category, there are four types of assistance, three of which are relevant to R&D on aluminum and chlor-alkali production processes. They are:

- (a) Procurements
- (b) Grants
- (c) Use of the national laboratories
- (d) Information transfer.

a. Procurements. Procurement contracts have often been used to support R&D objectives. They are not, however, likely to be appropriate at the present time as methods for stimulating R&D in the aluminum and chlor-alkali industries. This type of contract is designed for the procurement of materials, services, or data that will be used by the government. They are specifically not intended for use where the principal purpose of a government-private transaction is to stimulate research by a private contractor (22). Accordingly, this method for government financing of R&D is not suitable for stimulating research in the aluminum or chlor-alkali industries where direct government payment for the research is envisaged.

On the other hand, where information transfer is the selected R&D stimulus, a procurement contract will usually be required in order to obtain the information transfer services needed. This method of promoting R&D is discussed in subsection d. below.

b. Grants. Grants are generally used to stimulate R&D by university and other non-profit organizations; however, profit-making organizations may also receive them. Both basic research and demonstration projects are eligible, although grants are more commonly used for basic research.

Grants have several advantages and disadvantages from the public point of view. Like cooperative agreements,

they can be tailored to specific types of projects, although government regulations require a better definition of the type of project that is to be funded than is required for cooperative agreements.* The cost to the government is highly predictable, since grants are generally not amended to increase the funding level. Where high-technical-risk, major advances are considered to be in the public interest, but are too risky for private funding, this form of government-private arrangement may make possible research outcomes that private industry alone would never achieve.

Where the grants are applied to high-technical-risk projects, they will result in the transfer of a large proportion of the financial risk in the R&D outcome to the government. This may reduce the incentive to the grantee to extend its best effort. Grant funds are not reimbursed; should the project fail, the financial loss to the participating firm could be very small, thereby reducing the impetus to assign the best staff. This concern is magnified by the fact that government participation in a grant-funded project is minimal, and there is only limited opportunity to influence the outcome. This potential effect on incentive tends to increase the risk accepted by the government under this form of R&D assistance. It may be partially offset by granting funds only for key phases of a project, leaving a portion of the risk inherent in the overall project to the grantee.

Grants, like cooperative agreements, may be perceived as discriminatory by some members of the industry. This disadvantage can be partially overcome by offering all firms in an industry the opportunity to compete for the grants. Given the amount of private research underway on reducing the energy used in aluminum and chlor-alkali production processes, however, it may be difficult to select research foci and industrial awardees for grants without giving an appearance of favoritism.

The grant is applicable to low-risk, marginal technical improvements as well as to high-risk, major technical improvements. Its application to low-risk technical improvements should have the effect only of accelerating the process since, presumably, low-risk improvements would eventually be completed with private capital anyway. For this same reason, there would appear to be few occasions that would justify use of a stimulus that transfers a major part of the risk to the government solely to accelerate a low-risk project.

From the point of view of industry, grants can eliminate a major portion of the risk associated with a technically risky project. Grants, therefore, may enable

*Department of Energy regulations pursuant to the use of grants are outlined in 10 CFR 600.50-117.

private research labs to undertake research that otherwise would not receive serious consideration by corporate research directors. Grants to universities may be particularly useful where preliminary indication of the technical feasibility of a major but highly uncertain technical advance is sought.

As in the case of a cooperative agreement, the grantee does not gain proprietary rights in the data developed under the grant. Department of Energy regulations governing grants require that the government have unlimited rights in such data (23). This usually means that, if it cannot be demonstrated that the data were developed solely at private expense, such data will eventually become available to the firm's competitors through government auspices. If the grant funds are for an entire project, or a well-defined portion of it, as is usually the case with grants, it will be difficult to demonstrate that any portion of the data emanating from the project was developed exclusively at private expense. The offsetting advantage for this drawback is the early lead the grantee gains in experience with the new data.

Also noted earlier is the fact that the government is not required to exercise its rights to technical data. Although this option does not appear to be in common use by DOE, it leaves a range of possibilities open for negotiating relaxation of the government's rights in specific cases.*

The restrictions on patents for inventions and discoveries made under a government-funded grant are similar to those for cooperative agreements. As a matter of policy, the patent rights vest in the government (23). Inasmuch as the government's objective is usually commercialization, however, the waiver policy is liberal (7). Additionally, the grantee retains a certain scope of licensing rights even without waivers.**

c. Use of the National Laboratories. There may be some research objectives that are more appropriately assigned to a national laboratory. This approach would be appropriate where a desirable technical advance is possible but only at a large technical risk or where preliminary indication is needed of the technical feasibility of such an advance. Under these circumstances, the likelihood that private research investment would be forthcoming is low, yet the public interest might justify an initial public investment in the area.

*See page IV-5 above.

**The applicable patent rights and conditions are discussed in Department of Energy Procurement Regulations §9-9.1, especially 9-9.100, 9-9.107-3, 9-9.107-5, 9-9.109-6.

The national laboratories are capable of mounting research efforts of the largest scale, and their mandates have expanded in recent years to enable them to undertake a variety of types of projects. Basic research would appear, however, to be the type of work appropriate for a laboratory undertaking in the electrolytic processes area.

Through the government, the public accepts all of the technical risk for research done by the national laboratories. The government retains full control over the work, however, and usually has assurance that highly qualified research personnel will be assigned.

Given the private sector's independent interest in the more promising technical developments in the two industries under discussion, the labs will likely be most useful in undertaking research on the technologies that appear, at this point in time, to have less promise. On the other hand, major government investment in national laboratory research for these industries might be difficult to justify on the basis that there is adequate effort already in the private sector. These possible constraints suggest that the national labs should undertake research that is partitioned and narrowly focused.

As noted in an earlier section, Argonne National Laboratory is currently engaged in basic research to investigate selected aspects of producing aluminum using a sulfide intermediate.

d. Information Transfer. Traditionally, there is a long lag time between the development of a new technology or process in a heavy industry and its diffusion throughout the industry. In recent years, the typical lag time has become shorter; however, activities to accelerate the transfer of technical information on energy-saving opportunities to and within industries continue to be warranted. Given the plaint related in Section B that government restrictions on technical data and patent rights hinder timely spread and use of government-financed R&D results, a strong information transfer program may be particularly appropriate where R&D has been performed under such restrictions.

Information transfer activities typically consist of providing information and/or promotional materials and conducting promotional events.

Programs to provide technical R&D information have often created a standing information service of some form. The success of these services depends on how often they are used, which, in turn, depends upon the demand for the information they provide. If the demand does not exist beforehand,

it most likely cannot be stimulated in order to justify the program; as a result, the information service quickly becomes moribund. R&D information services also have the liability of being easily outdated. In the absence of active cooperation by researchers, which usually is the case, the service must depend upon published reports for its content. These reports often appear one to two years behind the actual research. Consequently, by the time the information service gets the information, it is two to three years old and has already circulated via other means to those who are interested in it.*

Another, perhaps more appropriate method of information transfer for the purpose of stimulating R&D is the use of promotional materials and events to accelerate the diffusion of information on selected R&D opportunities and results. In order to be effective, these promotional activities must capture and hold the attention of the executives who have the authority to make the desired investment decisions. Success in accomplishing this will be a function of the type, quality, and timing of the promotional materials/events.

The types of materials/events used can be tailored to the typical objectives of promotional activities, which are: (1) to attract the executive's attention, inform him that there is a message useful to him from a profit point of view, and to stimulate his readiness to listen or request more information; (2) to provide the more detailed information necessary to demonstrate the commercial advantages of the technology; and (3) to create a sense that an R&D investment needs to be made soon.

The type of materials and events designed to meet the first objective include: (1) announcements in magazines, newsletters, and journals read by executives and research directors; (2) direct mailings; and (3) presentations at conferences.

The second objective may be met through in-person briefings of key executives or mailings of specially prepared technical literature to research directors. Since briefings

**The Department of Energy's experience with the World Energy Data System (WENDS) is illustrative of these observations. This world energy R&D information retrieval system developed for DOE by Argonne National Laboratory was largely ignored by the DOE managers it was intended to serve, in part because they already had access to the same sources of information that the system would have used. The system now is inactive (Personal communication, Argonne National Laboratory; Hittman Associates, Identification and Evaluation of Foreign Energy Technology Areas, HIT-674, Vol. 1, March 1977).*

may be difficult to justify and/or arrange, an attractively prepared executive briefing report might be mailed to the executive whose interest is sought. For management officials whose responsibilities permit, or require, them to pay attention to technical detail, a more complete technical description could be prepared. As with an executive briefing report, however, a major ingredient in the success of the document would be the care with which it is prepared.

The third objective of the promotional activities, that of creating a sense that early R&D investment action is needed, may be introduced by the set of materials that are addressed to the second objective. The message can be reinforced by follow-up letters and reports of competitor R&D activity which could stimulate investment in new research.

As implied in the discussion of information services above, the currency of the information and the timing of the information transfer activity is important. Outdated information can create an impression that the service providing the information is of little value. On the other hand, a method of re-presenting old information that shows new opportunities inherent in it will offset the dated characteristic.

Information transfer activities are most effective if timed to coincide with periods of heightened receptivity on the part of the target audience. In the present case, conferences provide timely opportunities to present information on R&D opportunities and results.

Information transfer using promotional activities has several advantages over the use of standing information services. Promotional activities can be tailored to specific, preferred R&D outcomes. Compared to standing information services, they can be less expensive, although this will depend on the scope of the activities undertaken. They share with information services the disadvantage that they do not actively engage the commitment of industry. No actual research is performed as a direct result of the program expenditure. Industry can remain passive throughout the use of this approach. Promotional activities try to overcome this disadvantage, however, through a direct approach to their audience. Their principal advantage lies in this aggressive approach to attracting the interest of those who are able to make a commitment to R&D.

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