DOE/JPL/954343-80/18

PROCESS FEASIBILITY STUDY IN SUPPORT OF SILICON MATERIAL TASK I

Quarterly Technical Progress Report (XVIII) for December 1, 1979—February 29, 1980

By
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March 1980

Work Performed Under Contract No. NAS-7-100-954343

Lamar University
Chemical Engineering Department
Beaumont, Texas

U.S. Department of Energy

Solar Energy

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Microfiche $3.50

DOE/JPL/954343-80/18
Distribution Category UC-63b

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JPL Contract No. 954343

Contractual Acknowledgement

The JPL Low-Cost Solar Array Project is sponsored by the U.S. Department of Energy and forms part of the Solar Photovoltaic Conversion Program to initiate major effort toward the development of low-cost solar arrays. This work was performed for the Jet Propulsion Laboratory, California Institute of Technology by agreement between NASA and DOE.

Approval Signature Carl L. Yaws

ACKNOWLEDGEMENT

The authors wish to acknowledge the valuable help and contributions of the following in the performance of this work:

Faculty-Staff

LARRY L. DICKENS
C. S. FANG
FRED H. PITTS
KEITH C. HANSEN

Graduate-Student Assistants

PRABODH M. PATEL
PRAFUL N. SHAH
STEVE HAO CHANG
HARRY YU
LEE-HSIN TSAO

ABSTRACT

Analyses of process system properties were continued for important chemical materials involved in the several processes under consideration for semiconductor and solar cell grade silicon production. Major activities were devoted to physical, thermodynamic and transport property data for silicon. Property data are reported for vapor pressure, heat of vaporization heat of sublimation, liquid heat capacity and solid heat capacity as a function of temperature to permit rapid usage in engineering.

Chemical engineering analysis of the HSC process (Hemlock Semiconductor Corporation) for production of silicon was initiated. The process is based on hydrogen reduction of dichlorosilane (DCS) to produce the polysilicon. The chemical vapor deposition reaction for DCS is faster in rate than the conventional process route which utilizes trichlorosilane (TCS) as the silicon raw material. Status and progress are reported for primary activities of base case conditions (30%), reaction chemistry (25%) and process flow diagram (20%). Discussions with HSC and construction of a process flow diagram are in progress.

Preliminary economic analysis of the BCL process (case B) was completed. Cost analysis results are presented based on a preliminary process design of a plant to produce 1,000 metric tons/year of silicon. Fixed capital investment for the plant is $14.35 million (1980 dollars) and product cost without profist is 11.08 $/kg of silicon (1980 dollars). Cost sensitivity analysis indicate that the product cost is influenced most by plant investment and least by labor. For profitability, a sales price of 14 $/kg (1980 dollars) gives a 14% DCF rate of return on investment after taxes.

TABLE OF CONTENTS

I. PROCESS SYSTEM PROPERTIES ANALYSIS (TASK 1)

During this reporting period, analyses were continued for process system properties of chemical materials important in the production of silicon. Primary progress and status are reported for physical, thermodynamic, and transport properties of silicon.

PHYSICAL PROPERTIES (TABLE I-1)

Experimental values for the melting point have been reported (1, 32, 49, 67, 110); however, all other values have been calculated. Estimated values for the boiling point range from 2285°C to 3267°C (10, 31, 52, 55, 109, 124, 125, 137). Our value is estimated to give a reasonable computer fit to the available vapor pressure data. Estimated values of critical properties are reported by van Laar's calculation (5, 34, 43, 44, 101, 125,) Baibus (4) and Gates and Thodos (31) reported in Table I-1). Solid properties listed in Table I-1 are at room temperature while liquid properties are at the melting point.

VAPOR PRESSURE (FIGURE I-1)

Recent vapor pressure data reported by American (1, 18) and British (6) workers was selected and extended using the YSSP vapor pressure correlation (157):

$$\log P_V = A + \frac{B}{T} + C \log T + DT + ET^2$$

where P_V is the vapor pressure of saturated liquid, mm Hg; T is temperature, °K; and A, B, C, D and E are correlation constants derived using a generalized least squares program. Other data (10, 125, 142) was not used because of high percentage error which is reported to be due to extensive reaction of the silicon (54, 165). For the 44 experimental data points used (which are all in the range below 0.2 mm Hg) the average absolute deviation was 17%.

HEAT VAPORIZATION (FIGURE I-2)

Heat of vaporization values of about 3850 cal/gm are available (1, 6, 18, 55) as well as older (10, 125a, 147) and Russian (142) values of about 3170 cal/gm. From the vapor pressure data near the melting point, the heat of vaporization was determined using the Clausius-Clapyron equation. Using these values, Watson's correlation (165) was used to extend the heat of vaporization to the boiling point.

$$\Delta H_v = \Delta H_{v_1} \left[\frac{7500 - T}{7500 - T_1} \right]^n \qquad (1\text{-}2)$$

where n = 0.38 and all other terms have their usual meanings. The calculated values give a 1.3% absolute percentage deviation with the five experimental references giving values near 3850 cal/gm near the melting point.

HEAT OF SUBLIMATION (FIGURE I-3)

Heat of sublimation based on limited data have been reported recently in the literature (18, 54, 106). Using the YSSP correlation of vapor pressure data (as described earlier), heats of sublimation were calculated using the Clausius-Clapeyron equation (123):

$$\Delta H_{sub} = P\Delta V_{sub} \frac{\delta P}{\delta T} \qquad \text{(I-3)}$$

where ΔH_{sub} is the heat of sublimation, cal/gr-mol; P is the vapor pressure, atm; and $\Delta V_{sub} = V_{gas} - V_{solid}$. The derivative, $\delta P/\delta T$, was determined from differentiation of the YSSP vapor pressure equation. Considering the possible inaccuracy in the extrapolation of very low vapor pressures at low temperatures, these values should be considered only order-of-magnitude calculations below 600°C.

HEAT CAPACITY (FIGURES I-4 & I-5)

Liquid heat capacities have been reported from experiments done in the range from the melting point to about 200°C above the melting point (67,100). The values of Kantur (67) were selected because the temperature range was significantly greater with the temperatures appearing to be more accurately determined. The average values of heat capacity and temperature was taken as a reference point and the values were extended over the liquid range using the relationship:

Liquid Heat Capacity x Liquid Density = constant (I-4)

Calculated values agree within two percent of the values published in the experimental work (67).

Solid heat capacities have been reported by many authors (144,138, 55, 34, 96, 164, 62, 115, and others) which give similar values. The JANAF and Touloukian values (138, 144) were selected.

TABLE I-1

PHYSICAL PROPERTIES AND CRITICAL CONSTANTS OF SILICON

No.	Identification	Silicon
1.	Symbol	Si
2.	State (std. cond.)	Solid
3.	Atomic Weight	28.086
4.	Boiling Point, b.p., °C	2,878*
5.	Melting Point, m.p., °C	1,412 ± 2
6.	Critical Temperature, T_C, °C	4,886*
7.	Critical Pressure, P_C, atm	530*
8.	Critical Volume, V_C, cm^3/gr mol	232.6*
9.	Critical Density, ρ_C, gr/cm^3	0.1207*
10.	Vapor Pressure, mm Hg	2.8×10^{-4} (at m.p.)
11.	Heat of Vaporization, cal/gr	3,812 (at m.p.)
12.	Heat of Sublimation, cal/gr	4,075 (at m.p.)
13.	Heat of Fusion, cal/gr	264* (at m.p.)
14.	Liquid Heat Capacity, cal/gr-mol °C	6.755 (at m.p.)
15.	Solid Heat Capacity, cal/gr-mol °C	4.78 (at 25°C)
16.	Liquid Density, gr/cm^3	2.533 (at m.p.)
17.	Solid Density, gr/cm^3	2.329 (at 25°C)
18.	Percent Expansion on Freezing	10% (at m.p.)
19.	Surface Tension, dynes/cm	736 (at m.p.)
20.	Liquid Viscosity, centipoise	0.88 (at m.p.)
21.	Liquid Thermal Conductivity, cal/secxcmx°C	1.025×10^{-3} (at m.p.)
22.	Solid Thermal Conductivity, cal/secxcmx°C	0.353 (at 25°C)

*estimated

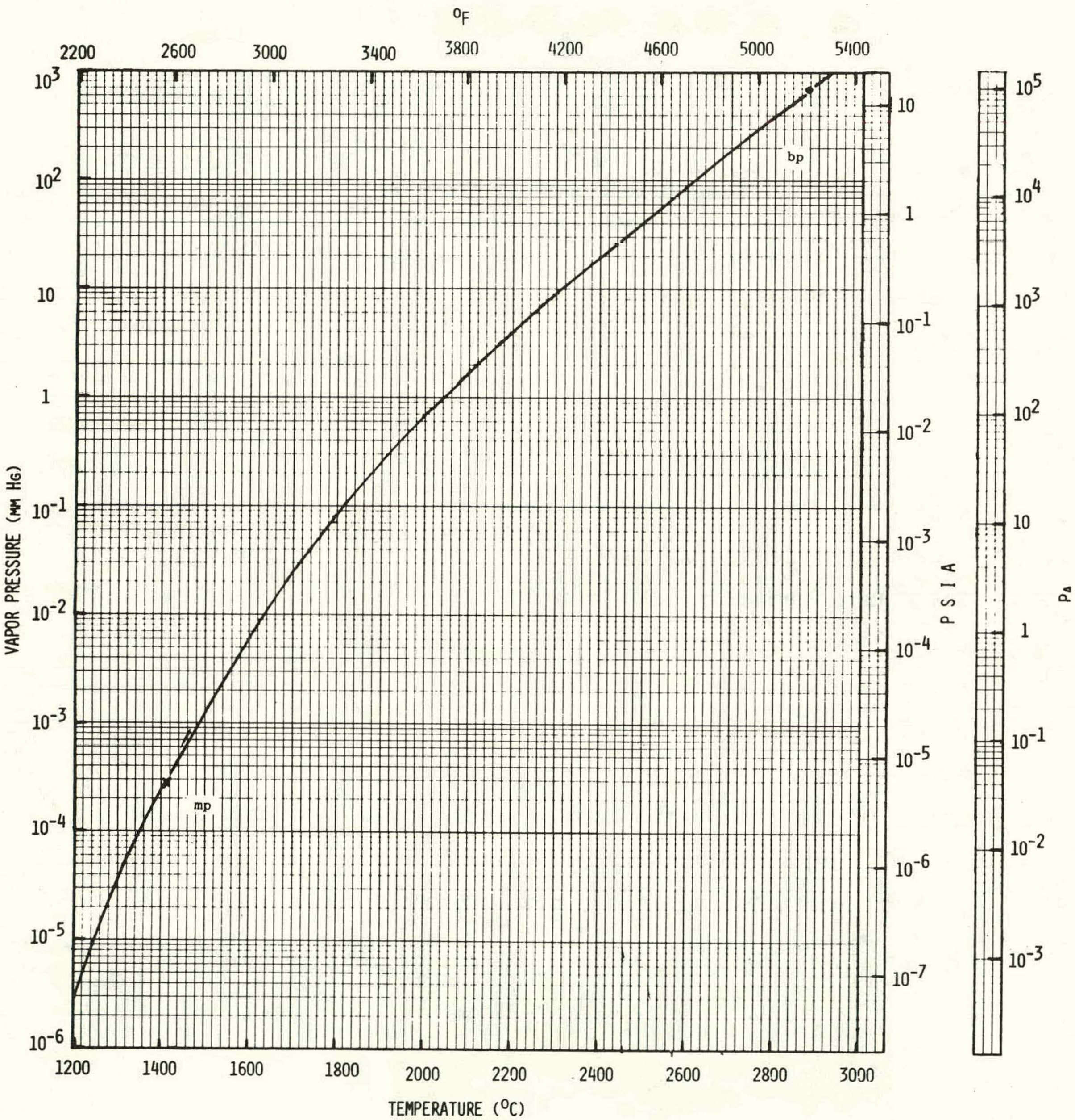


Figure I-1--Vapor Pressure vs. Temp. for Silicon

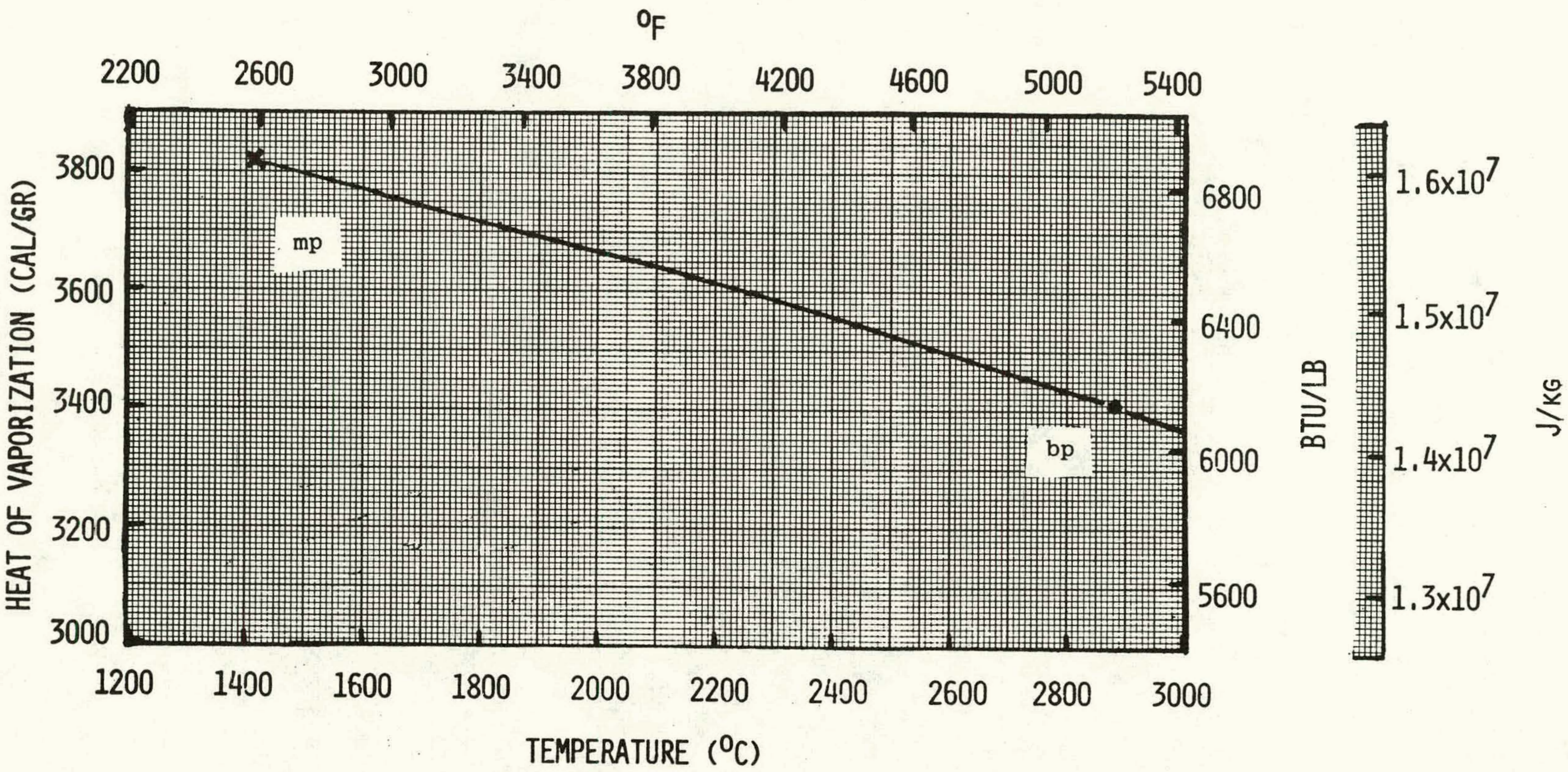


Figure I-2--Heat of Vaporization vs. Temp. for Silicon

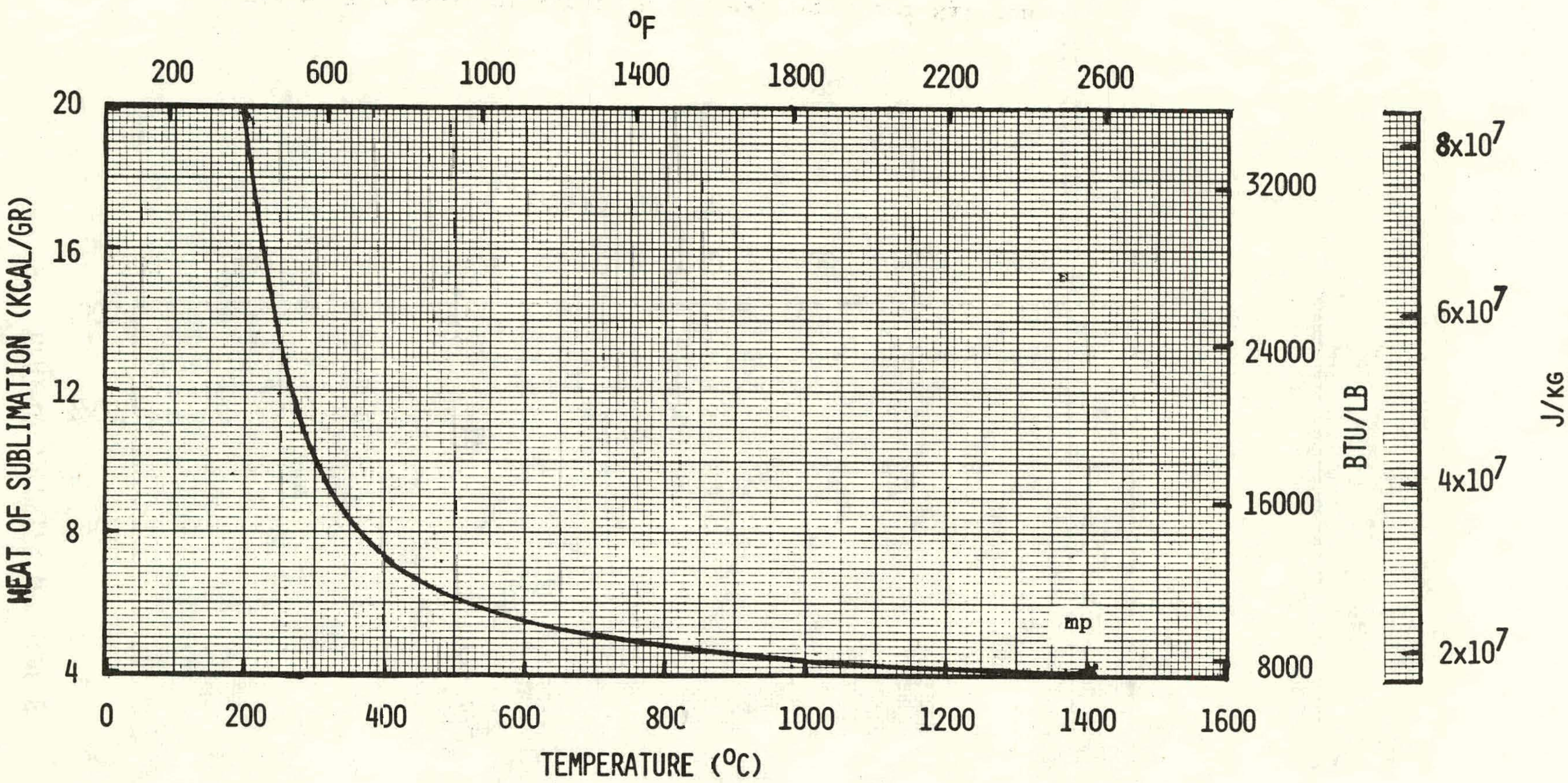


Figure I-3--Heat of Sublimation vs. Temp. for Silicon

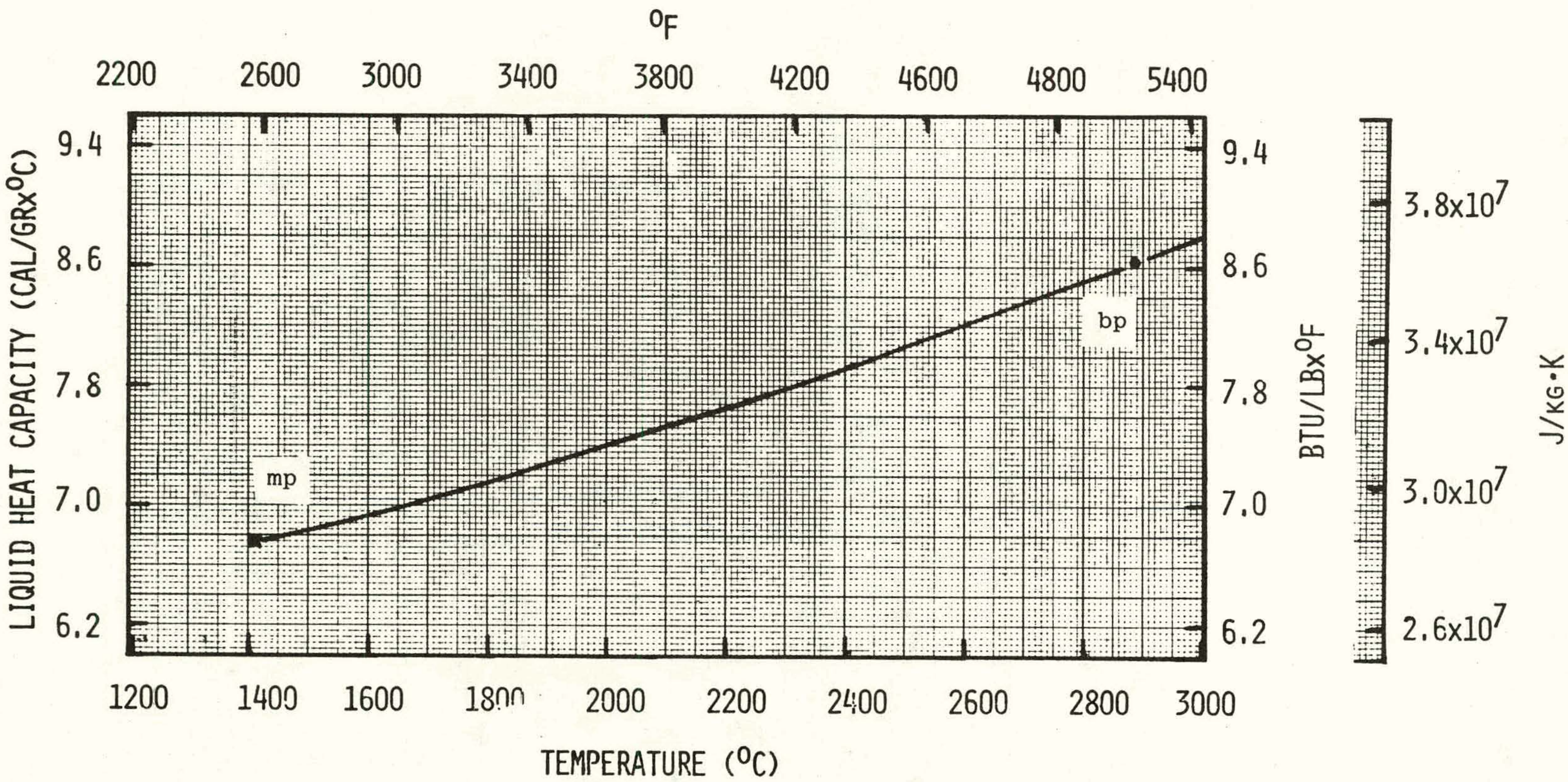


Figure I-4--Liquid Heat Capacity vs. Temp. for Silicon

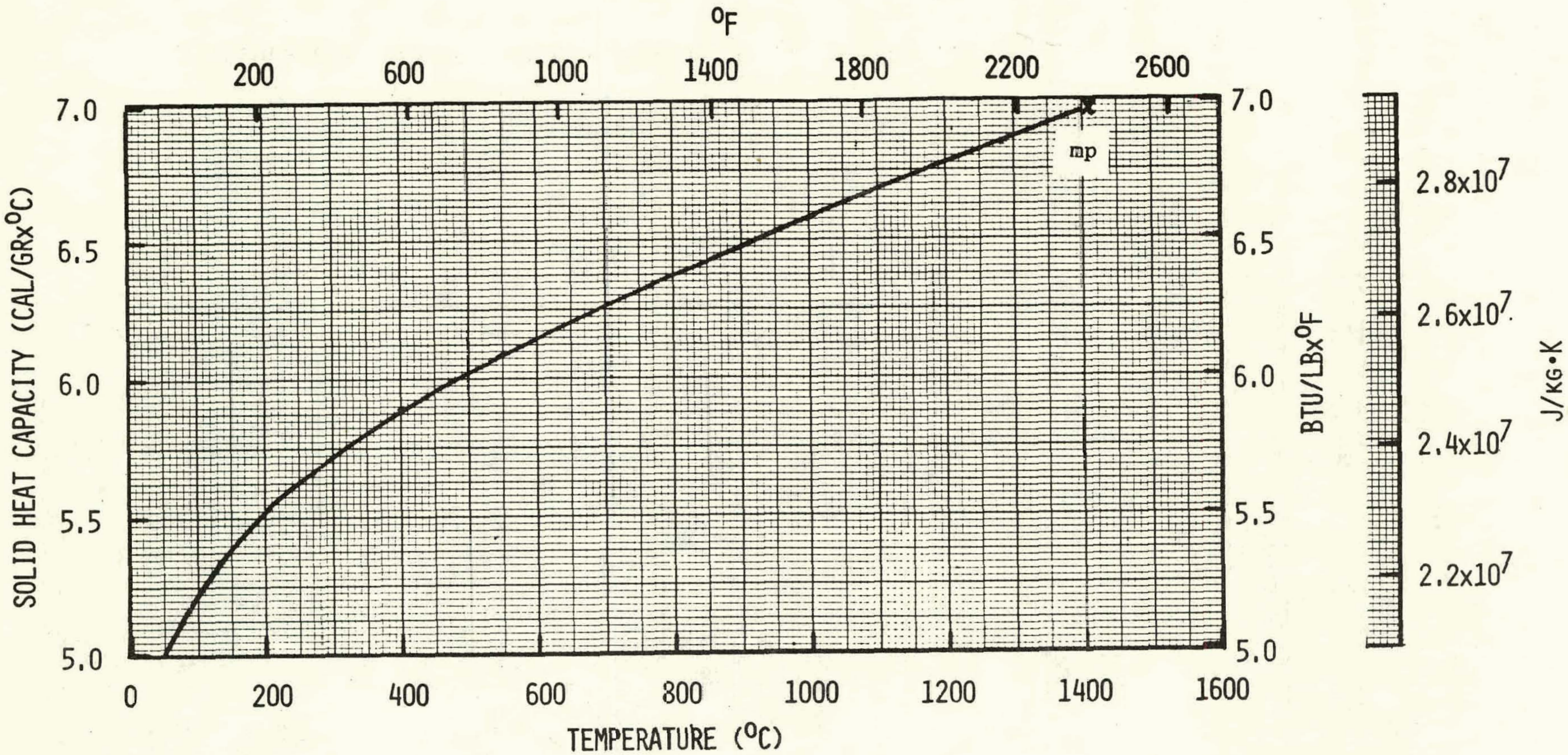


Figure 1-5--Solid Heat Capacity vs. Temp. for Silicon

II. CHEMICAL ENGINEERING ANALYSIS

A. HSC PROCESS

The chemical engineering analysis of the chlorosilane vapor deposition process for the production of low cost solar cell grade silicon has been initiated. Hemlock Semiconductor Corporation (HSC) has been contacted to discuss the process flow diagram for this chemical vapor deposition process. Construction of the flow sheet for preliminary engineering design has been started following initial discussions.

The HSC process is based on the chemical vapor deposition of dichlorosilane (DCS) with hydrogen to produce high purity polysilicon. This DCS deposition reaction rate is fast and has the following representative chemical reaction equation:

$$SiH_2Cl_2 + H_2 \rightarrow Si \downarrow + \text{By-products}$$

The above reaction equation may include several reaction steps. Chemical equilibrium is involved and in reality, several chlorosilanes (such as SiH_2Cl_2, $SiHCl_3$ and $SiCl_4$) are also present in the gas phase by products.

Primary activities in the HSC process are being devoted to establishing base case conditions, defining reaction chemistry and constructing process flow diagram. The status of the chemical engineering analysis and progress attained since the last reporting period are summarized below for the primary activities:

	Prior	Current
•Base Case Conditions	0%	30%
•Reaction Chemistry	0%	25%
•Process Flow Diagram	0%	20%

The detailed status is shown in Table IIA-1.0 for the major items comprising the preliminary process design for the chemical engineering analysis.

TABLE IIA-1.0 CHEMICAL ENGINEERING ANALYSES: PRELIMINARY PROCESS DESIGN ACTIVITIES FOR HSC PROCESS

Prel. Process Design Activity	Status
1. Specify Base Case Conditions	◐
1. Plant Size	◐
2. Product Specifics	◐
3. Additional Conditions	◐
2. Define Reaction Chemistry	◐
1. Reactants, Products	◐
2. Equilibrium	◐
3. Process Flow Diagram	◐
1. Flow Sequence, Unit Operations	◐
2. Process Conditions (T, P, etc.)	◐
3. Environmental	◐
4. Company Interaction (Technology Exchange)	◐
4. Material Balance Calculations	0
1. Raw Materials	0
2. Products	0
3. By-Products	0
5. Energy Balance Calculations	0
1. Heating	0
2. Cooling	0
3. Additional	
6. Property Data	0
1. Physical	0
2. Thermodynamic	0
3. Additional	0

Prel. Process Design Activity	Statu
7. Equipment Design Calculations	0
1. Storage Vessels	0
2. Unit Operations Equipment	0
3. Process Data (P, T, rate, etc.)	0
4. Additional	0
8. List of Major Process Equipment	0
1. Size	0
2. Type	0
3. Materials of Construction	0
8a. Major Technical Factors	0
(Potential Problem Areas)	0
1. Materials Compatibility	0
2. Process Conditions Limitations	0
3. Additional	0
9. Production Labor Requirements	0
1. Process Technology	0
2. Production Volume	0
10. Forward for Economic Analysis	0

0 Plan
◐ In Progress
● Complete

B. OTHER PROCESSES

Other processes (such as UCC silane process, BCL process, etc.) under consideration for solar cell grade silicon production are being monitored with respect to data relative to chemical engineering analysis.

III. ECONOMIC ANALYSIS (TASK 3)

A. BCL PROCESS (CASE B) - COST ANALYSIS

Major efforts were completed during this reporting period on the preliminary economic analysis for BCL process - Case B (one deposition reactor and two electrolysis cells).

A summation of the key results for the BCL process (Case B) is presented in the following table:

1. Process ....BCL process
2. Plant Size ....1,000 Metric Tons/year
3. Plant Product ....Silicon
4. Product Form ....Silicon Granules
5. Plant Investment........................$11,790.000/$16,500.000
   (1975 dollars) (1980 dollars)

Fixed Capital	$10.25 Mega	$14.35 Mega
Working Capital (15%)	$ 1.54 Mega	$ 2.15 Mega
Total	$11.79 Mega	$16.50 Meha
	1975 dollars)	(1980 dollars)

6. Product Cost (No Profit)...............$ 7.91 $/kg $11.08 $/kg
   (1975 dollars) (1980 dollars)

7. Inflation Factor (1975 to 1980).....1.4

The detailed status sheet is shown in Table IIIA-1.0, and is representative of various subitems that make up the preliminary economic analysis activities. The detailed results from the preliminary economic analysis are presented in a tabular format. The guide for the tabular format is given below:

- .Preliminary Economic Analysis Activities ....Table IIIA-1.0
- .Process Design Inputs..............................Table IIIA-1.1
- .Base Case Conditions ....Table IIIA-1.2
- .Raw Material Cost ....Table IIIA-1.3
- .Utility Cost ....Table IIIA-1.4
- .Major Process Equipment Cost.......................Table IIIA-1.5
- .Production Labor Cost..............................Table IIIA-1.6
- .Plant Investment...................................Table IIIA-1.7
- .Total Product Cost.................................Table IIIA-1.8

The results indicate that the product cost without profit is $11.08 $/kg of Silicon (1980 dollars) for the Case B of BCL proces.

CASE B

TABLE IIIA-1.0

ECONOMIC ANALYSES:
PRELIMINARY ECONOMIC ANALYSIS ACTIVITIES FOR BCL PROCESS
(BATTELLE COLUMBUS LABORATORIES)

Prel. Process Economic Activity	Status
1. Process Design Inputs	●
1. Raw Material Requirements	●
2. Utility Requirements	●
3. Equipment List	●
4. Labor Requirements	●
2. Specify Base Case Conditions	●
1. Base Year for Costs	●
2. Appropriate Indices for Costs	●
3. Additional	●
3. Raw Material Costs	●
1. Base Cost/Lb. of Material	●
2. Material Cost/Kg of Silicon	●
3. Total Cost/Kg of Silicon	●
4. Utility Costs	●
1. Base Cost for Each Utility	●
2. Utility Cost/Kg of Silicon	●
3. Total Cost/Kg of Silicon	●
5. Major Process Equipment Costs	●
1. Individual Equipment Cost	●
2. Cost Index Adjustment	●
6. Production Labor Costs	●
1. Base Cost Per Man Hour	●
2. Cost/Kg Silicon Per Area	●
3. Total Cost/Kg Silicon	●
7. Estimation of Plant Investment	●
1. Battery Limits Direct Costs	●
2. Other Direct Costs	●
3. Indirect Costs	●
4. Contingency	●
5. Total Plant Investment (Fixed Capital)	●
8. Estimation of Total Product Cost	●
1. Direct Manufacturing Cost	●
2. Indirect Manufacturing Cost	●
3. Plant Overhead	●
4. By-Product Credit	●
5. General Expenses	●
6. Total Cost of Product	●

O Plan
◐ In Progress
● Complete

TABLE IIIA-1.1

PROCESS DESIGN INPUTS FOR
BCL PROCESS (BATTELLE COLUMBUS LABORATORIES)

1. Raw Material Requirements
   -Silicon tetrachloride, zinc, lime, argon and nitrogen
   -see table for "Raw Material Cost"

2. Utility
   -electricity, steam, cooling water and process water
   -see table for "Utility Cost"

3. Equipment List
   -70 plus pieces of major process equipment
   -process vessels, heat exchangers, reactor, etc.

4. Labor Requirements
   -production labor for purification, deposition, electrolysis, etc.
   -see table for "Production Labor Cost"

CASE B

TABLE IIIA-1.2
BASE CASE CONDITION FOR BCL PROCESS
(BATTELLE COLUMBUS LABORATORIES)

1. Capital Equipment

   -January 1975 Cost Index for Capital Equipment Cost
   -January 1975 Cost Index Value = 430

2. Utilities

   -Electrical, Steam, Cooling Water, Nitrogen
   -January 1975 Cost Index (U. S. Dept. Labor)
   -Values determined by literature search and summarized in cost standardization work

3. Raw Material Cost

   -Chemical Marketing Reporter
   -January 1975 Value
   -Raw Material Cost Index for Industrial Chemicals
   -1975 Cost Index Value = 206.9 (Wholesale Price Index, Producer Price Index)

4. Labor Cost

   -Average for Chemical Petroleum, Coal and Allied Industries (1975)
   -Skilled \$6.90/hr

5. Update to 1980

   -historically cited 1975 dollars (LSA project)
   -DOE decision to change to 1980 dollars (JPL, 6/22/79)
   -reports to reflect <u>both</u> 1975 and 1980 dollars (JPL, 6/22/79)
   -inflation factor of 1.4 to be used (JPL, 6/22/79)

CASE B

Table IVA-1.3

RAW MATERIAL COST FOR BCL PROCESS
(BATTELLE COLUMBUS LABORATORIES)

	Raw Material	Requirement lb/KG of Si	$/lb of Material	Cost $/KG of Si
1.	Silicon Tetrachloride ($SiCl_4$)	15.68	0.135	2.117
2.	Zinc (Zn)	0.54	0.38	0.205
3.	Hydrate Lime ($Ca(OH)_2$)	2.85	0.015	0.043
4.	Argon (Ar)	3.1 SCF	0.016/SCF	0.050
5.	Nitrogen (N_2)	7.6 SCF	0.003/SCF	0.023
			Sub Total	2.438
6.	Chlorine (Cl_2)	-10.46[1]	0.0332	-0.347
			TOTAL	2.091 (1975 dollars)
				x 1.4 inflation
				2.927 (1980 dollars)

Note:

1. This number is the result of by-product rate minus reactor chlorination rate, i.e., 11.12 - 0.66 lb. of Cl_2/KG Si.

CASE B

Table IIIA-1.4
UTILITY COST FOR BCL PROCESS
(BATTELLE COLUMBUS LABORATORIES)

	Utility	Requirement/KG of Silicon	Cost of Utility	Cost $/KG of Silicon
1.	Electricity	30.92 KW-HR	0.0324 $/KW-HR	1.0018
2.	Steam	9.67 pounds	1.35 $/Mlb	0.0131
3.	Cooling Water	37.88 Gallons	0.09 $/Mgal	0.0034
4.	Process Water	24.20 Gallons	0.405 $/Mgal	0.0098
5.	Refrigerant	2.38 MBtu	10.50 $/MMBtu	0.0250
			TOTAL	1.0531 (1975 dollars
				x 1.4 inflation
				1.4743 (1980 dollars

CASE B

TABLE IIIA-1.5

ESTIMATED COST OF MAJOR PROCESS EQUIPMENT FOR BCL PROCESS
(BATTELLE COLUMBUS LABORATORIES)

	Equipment	Purchased Cost, $1,000
1.	(D-01) Light End Distillation Column	55.6
2.	(D-02) Heavy End Distillation Column	55.6
3.	(A-01) Primary $SiCl_4$ Vent Scrubber	0.8
4.	(A-02) Final $SiCl_4$ Vent Scrubber	11.1
5.	(H-01) L. E. Column Feed Heater	7.8
6.	(H-02) L. E. Column Reboiler	2.2
7.	(H-03) L. E. Column Condenser	2.3
8.	(H-04) H. E. Column Feed Heater	7.8
9.	(H-05) H. E. Column Reboiler	2.4
10.	(H-06) H. E. Column Condenser	2.3
11.	(H-07) $SiCl_4$ Vent Condenser	11.8
12.	(H-08) $SiCl_4$ Vaporizer	6.7
13.	(H-09) Reactor Condensers (2)	144.2
14.	(H-10) Reactor $ZnCl_2$ Strippers (2)	21.1
15.	(H-11) $SiCl_4$ Condenser	20.5
16.	(H-12) Cell $ZnCl_2$ Stripper	10.9
17.	(H-13) Therminol Cooler (Cold Circuit)	3.8
18.	(H-14) Therminol Cooler (Hot Circuit)	9.1
19.	(H-15) Start-up Heater	9.6
20.	(H-16) Silicon Product Coolers (2)	5.8
20a.	(H-17) Chlorination Cooler	15.9
20b.	(H-18) Cell Gas Cooler	18.7
21.	(T-01) $SiCl_4$ Storage Tank	33.6
22.	(T-02) $SiCl_4$ Emergency Storage Tank	33.6
23.	(T-03) L. E. Column Reflux Drum	6.7

TABLE IIIA-1.5 (Continued)

24.	(T-04) Surge Tank	19.0
25.	(T-05) Sump Tank	19.0
26.	(T-06) H. E. Column Reflux Drum	6.7
27.	(T-07) Pure $SiCl_4$ Storage Tank	28.8
28.	(T-08) Electrolysis Feed Tank	46.0
29.	(T-09) Molten Zinc Storage Tank	86.9
30.	(T-10) Therminol Head Tank	3.8
31.	(T-11) Therminol Drain Down Tank	5.3
32.	(T-12) Chlorine Supply Tank	2.4
33.	(T-13) Lime Solution Storage Tank	6.8
34.	(P-01) Purification Feed Pump	3.7
35.	(P-02) L. E. Column Feed Pump	8.4
36.	(P-03) L. E. Column Reflux Pump	8.4
37.	(P-04) Surge Tank Pump	9.8
38.	(P-05) Sump Pump	3.7
39.	(P-06) L. E. Column Bottom Pump	12.0
40.	(P-07) H. E. Column Reflux Pump	8.4
41.	(P-08) H. E. Column Bottom Pump	10.9
42.	(P-09) $SiCl_4$ Vaporizer Feed Pump	4.8
43.	(P-10) Reactor Condenser Circulation Pumps (2)	10.9
44.	(P-11) Cold Circuit Pump	6.7
45.	(P-12) Hot Circuit Pump	13.9
46.	(P-13) Primary Scrubber Recirculation Pump	0.9
47.	(P-14) Primary Scrubber Lower-loop Recirculation Pump	1.4
48.	(P-15) Primary Scrubber Upper-loop Recirculation Pump	1.5
49.	(P-16) Lime Solution Metering Pump	1.4

CASE B

TABLE IIIA-1.5 (Continued)

50.	(F-01) L. E. Column Feed Filter	0.9
51.	(F-02) L. E. Column Reflux Filter	0.9
52.	(F-03) H. E. Column Feed Filter	0.9
53.	(F-04) H. E. Column Reflux Filter	0.9
54.	(F-05) Therminol Cooler Blower Filter	0.7
55.	(R-01) Fludized Bed Reactors	149.4
56.	(FN-01) Furnaces	268.5
57.	(B-01) Seed Addition Hoppers	7.3
58.	(B-02) Si Product Hoppers (4)	14.4
59.	(B-03) Zinc Hopper	2.4
60.	(C-01) Therminol Cooler Blower	4.8
61.	(C-02) Scrubber Vent Blower	5.4
62.	(E-01) Eductors (2)	1.3
63.	(EC-01) Electrolysis Cells (2)	286.5
64.	(PW-01) Power Supply and Bus	105.9
65.	(VP-01) Zinc Vaporizers	109.1
	TOTAL	1,790.7 (1975 dollars)
		x 1.4 inflation
		2,507.0 (1980 dollars)

CASE B

TABLE IIIA-1.6

PRODUCTION LABOR COST FOR BCL PROCESS
(BATTELLE COLUMBUS LABORATORIES)

	Section	Labor Man-Hr/Kg Si	Labor Cost $/Man-Hr	Cost $/Kg Si
1.	Purification	0.01402	6.90	0.0968
2.	Deposition	0.01402	6.90	0.0968
3.	Electrolysis	0.02103	6.90	0.1451
4.	Waste Treatment	0.00701	6.90	0.0484
5.	Product Handling	0.00701	6.90	0.0484
			TOTAL	0.4355 (1975 dollars)
				x 1.4 inflation
				0.6097 (1980 dollars)

Note: Costs are 1975 Dollars

CASE B

TABLE IIIA-1.7

ESTIMATION OF PLANT INVESTMENT FOR BCL PROCESS
(BATTELLE COLUMBUS LABORATORIES)

		Investment $1000	
1.	DIRECT PLANT INVESTMENT COSTS		
	1. Major Process Equipment Cost	1,790.7	
	2. Installation of Major Process Equipment	770.0	
	3. Process Piping, Installed	1,325.1	
	4. Instrumentation, Installed	340.2	
	5. Electrical, Installed	179.1	
	6. Process Buildings, Installed	179.1	
1a.	SUBTOTAL FOR DIRECT PLANT INVESTMENT COSTS (PRIMARILY BATTERY LIMIT FACILITIES)	4,584.2	
2.	OTHER DIRECT PLANT INVESTMENT COSTS		
	1. Utilities, Installed	859.5	
	2. General Service, Site Development, Fire Protection, etc.	214.9	
	3. General Buildings, Offices, Shops, etc.	250.7	
	4. Receiving, Shipping Facilities	376.1	
2a.	SUBTOTAL FOR OTHER DIRECT PLANT INVESTMENT COSTS (PRIMARILY OFFSITE FACILITIES OUTSIDE BATTERY LIMITS)	1,701.2	
3.	TOTAL DIRECT PLANT INVESTMENT COST, 1a + 2a	6,285.4	
4.	INDIRECT PLANT INVESTMENT COSTS		
	1. Engineering, Overhead, etc.	984.9	
	2. Normal Cont. for Floods, Strikes, etc.	1,271.4	
4a.	TOTAL INDIRECT PLANT INVESTMENT COST	2,256.3	
5.	TOTAL DIRECT AND INDIRECT PLANT INVESTMENT COST, 3 + 4a	8,541.6	
6.	OVERALL CONTINGENCY, % of 5	1,708.3	
7.	FIXED CAPITAL INVESTMENT FOR PLANT, 5 + 6	10,250.0	(1975 dollars)
		x 1.4	inflation
		14,350.0	(1980 dollars)

CASE B

TABLE IIIA-1.8

ESTIMATION OF TOTAL PRODUCT COST FOR BCL PROCESS
(BATTELLE COLUMBUS LABORATORIES)

	$/KG of Si
1. Direct Manufacturing Cost (Direct Charges)	
1. Raw Materials	2.091
2. Direct Operating Labor	0.436
3. Utilities	1.053
4. Supervision and Clerical	0.065
5. Maintenance and Repairs	1.025
6. Operating Supplies	0.205
7. Laboratory Charge	0.065
2. Indirect Manaufacturing Cost (Fixed Charges)	
1. Depreciation	1.025
2. Local Taxes	0.205
3. Insurance	0.103
3. Plant Overhead	0.608
4. By-Product Credit	-----
4a. Total Manufacturing Cost, 1 + 2 + 3 + 4	6.881
5. General Expenses	
1. Administration	0.413
2. Distribution and Sales	0.413
3. Research and Development	0.206
6. Total Cost of Product, 4a + 5	7.913 (1975 dollars)
	x 1.4 inflation
	11.078 (1980 dollars)

B. BCL PROCESS (CASE B) - COST SENSITIVITY ANALYSIS

Major efforts centered on cost sensitivity analysis of the BCL process including the influence of raw materials, labor, utilities and capital investment.

Detailed status sheet (Table IIIB-1.0) shows status and progress for cost sensitivity analysis.

The preliminary cost sensitivity analysis is performed to determine the influence of cost parameters on the economics of producing silicon by this new technology. The cost sensitivity results are given in Figure IIIB-1.1 in which product cost ($/kg Si) is plotted versus variation (-100% to 0% to +100%) of the primary cost parameters (plant investment, raw materials, labor and utilities). The 0% variation represents the base case. The -100% variation corresponds to the case of no costs for the parameter; and the +100% represents the case for a doubling of cost for each parameter. The plot illustrates that the cost parameter influence on product cost is : plant investment (most) raw materials (intermediate), utilities (intermediate) and labor (least).

The cost and profitability analysis summary is presented in Table IIIB-1.1 for both 1975 and 1980 time periods. The sales price of polysilicon at various rates or return for both profitability methods (%ROI and %DCF) is shown in the lower half of the table. The results indicate a sales price of 10 $/kg of silicon (1975 dollars) or 14 $/kg (1980 dollars), at a 14% %DCF rate of return after taxes for the process.

The effect of inflation (higher costs for raw material, utilities, labor, etc.) is shown in Figure IIIB-1.2. For the levels (0%, 5%, 7%, and 10% inflation) for the 1980-1995 time period.

CASE B

TABLE IIIB-1.0 COST SENSITIVITY ANALYSIS:
PRELIMINARY COST SENSITIVITY ACTIVITIES FOR BCL PROCESS (BATTELLE COLUMBUS LABORATORIES)

Prel. Sensitivity Activity	Status
1. Specify Base Case Conditions	●
1. Process	●
2. Plant Size	●
3. Product	●
4. Cost Data	●
2. Return on Original Investment	●
1. Capital Investment	●
2. Taxes	●
3. % ROI	●
3. Discounted Cash Flow Rate of Return	●
1. Capital Investment	●
2. Taxes	●
3. % DCF	●
4. Plant Investment Cost Variation	●
1. Major Process Equipment	●
2. Installation, Pipint	●
3. Instrumentation, Buildings	●
4. Offsites	●
5. Indirects, Engineering	●
6. Fixed, Working Capital	●
7. Other	●
5. Raw Material Cost Variation	●
1. Major Raw Materials	●
2. Waste Treatment	●
3. By-Product	●

Prel. Sensitivity Analysis	Status
6. Utilities Cost Variation	●
1. Steam	●
2. Electricity	●
3. Cooling Water	●
4. Process Water	●
5. Other	●
7. Labor Cost Variation	●
1. Production Labor	●
2. Labor Rate	●
3. Staffing Estimate	●
8. Effect of Inflation	●
1. Rate	●
2. Future	●
9. Cost and Profitability Analysis Summary	●
1. Plant Investment	●
2. Product Cost	●
3. Sales Price (Profit)	●

O Plan
◐ In Progress
● Complete

CASE B

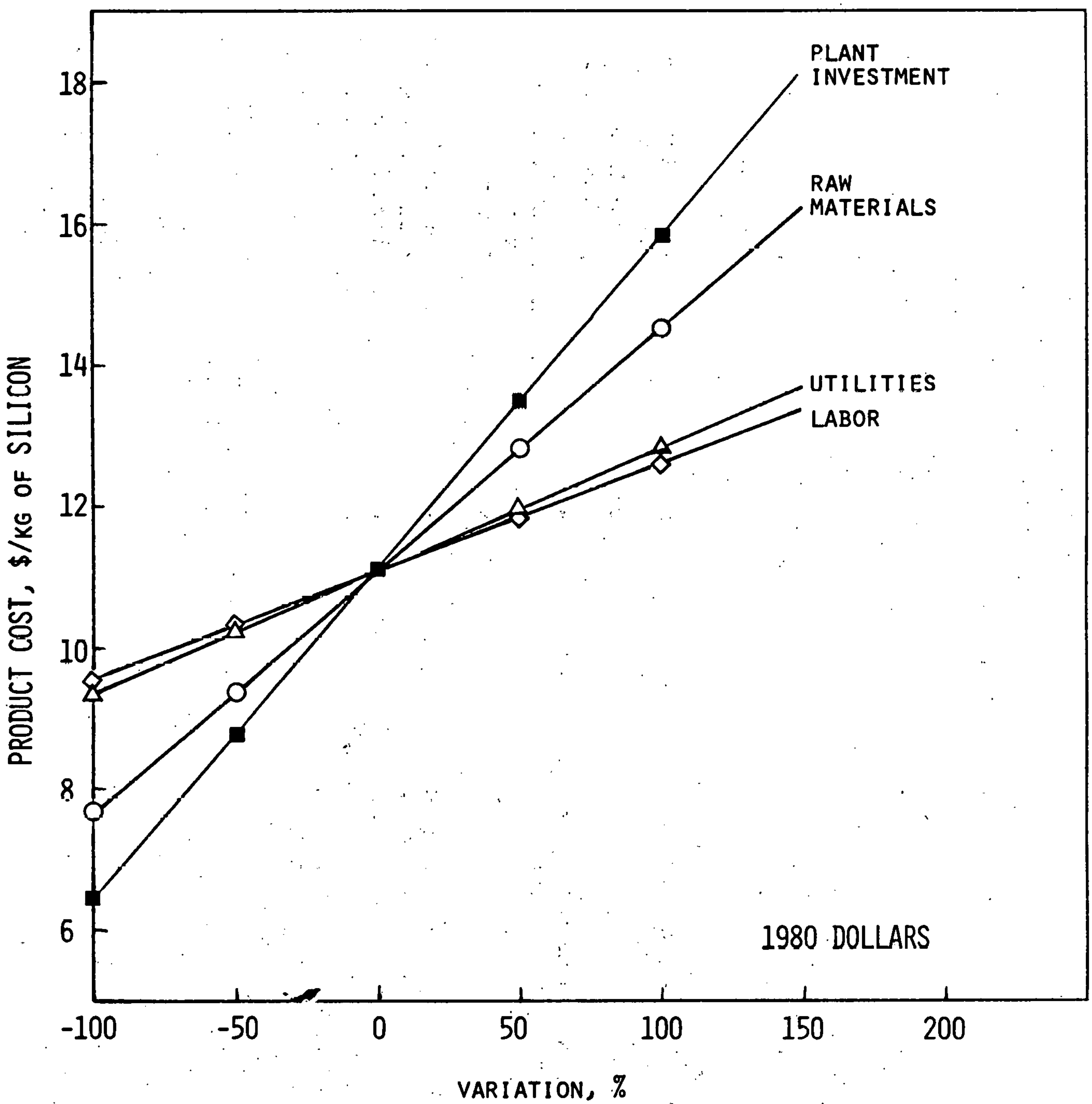


FIGURE IIIB-1.1 COST SENSITIVITY ANALYSIS OF BCL PROCESS (CASE B)

CASE B

TABLE IIIB-1.1

COST AND PROFITABILITY ANALYSIS SUMMARY FOR BCL PROCESS

(Case B)

1. Process....................................BCL Process
2. Plant Size.................................1,000 Metric Tons/year
3. Plant Product..............................Silicon
4. Product Form...............................Silicon Granules
5. Plant Investment...........................$11,790,000/$16,500,000 (1975 dollars) (1980 dollars)

Fixed Capital		$10.25 Mega	$14.35 Mega
Working Capital (15%)		1.54 Mega	2.15 Mega
	TOTAL	$11.79 Mega	$16.50 Mega
		(1975 dollars)	(1980 dollars)

6. Product Cost...............................7.19 $/Kg (1975 dollars)
7. Tax Rate (Federal).........................46%
8. Return on Original Investment, after taxes (%ROI)

	Sales Price $/Kg of Silicon (1975 dollars)	Sales Price $/Kg of Silicon (1980 dollars)
0% ROI..............	7.91	11.08
5% ROI..............	9.00	12.61
10% ROI..............	10.10	14.13
15% ROI..............	11.19	15.66
20% ROI..............	12.28	17.19
25% ROI..............	13.37	18.72
30% ROI..............	14.46	20.25
40% ROI..............	16.64	23.30

9. Discounted Cash Flow Rate of Return, after taxes (%DCF)

	Sales Price $/Kg of Silicon (1975 dollars)	Sales Price $/Kg of Silicon (1980 dollars)
0% DCF..............	7.91	11.08
5% DCF..............	8.62	12.06
10% DCF..............	9.39	13.14
15% DCF..............	10.22	14.31
20% DCF..............	11.11	15.56
25% DCF..............	12.04	16.86
30% DCF..............	13.01	18.21
40% DCF..............	15.02	21.03

Based on 10 year project life and 10 year straight line depreciation.

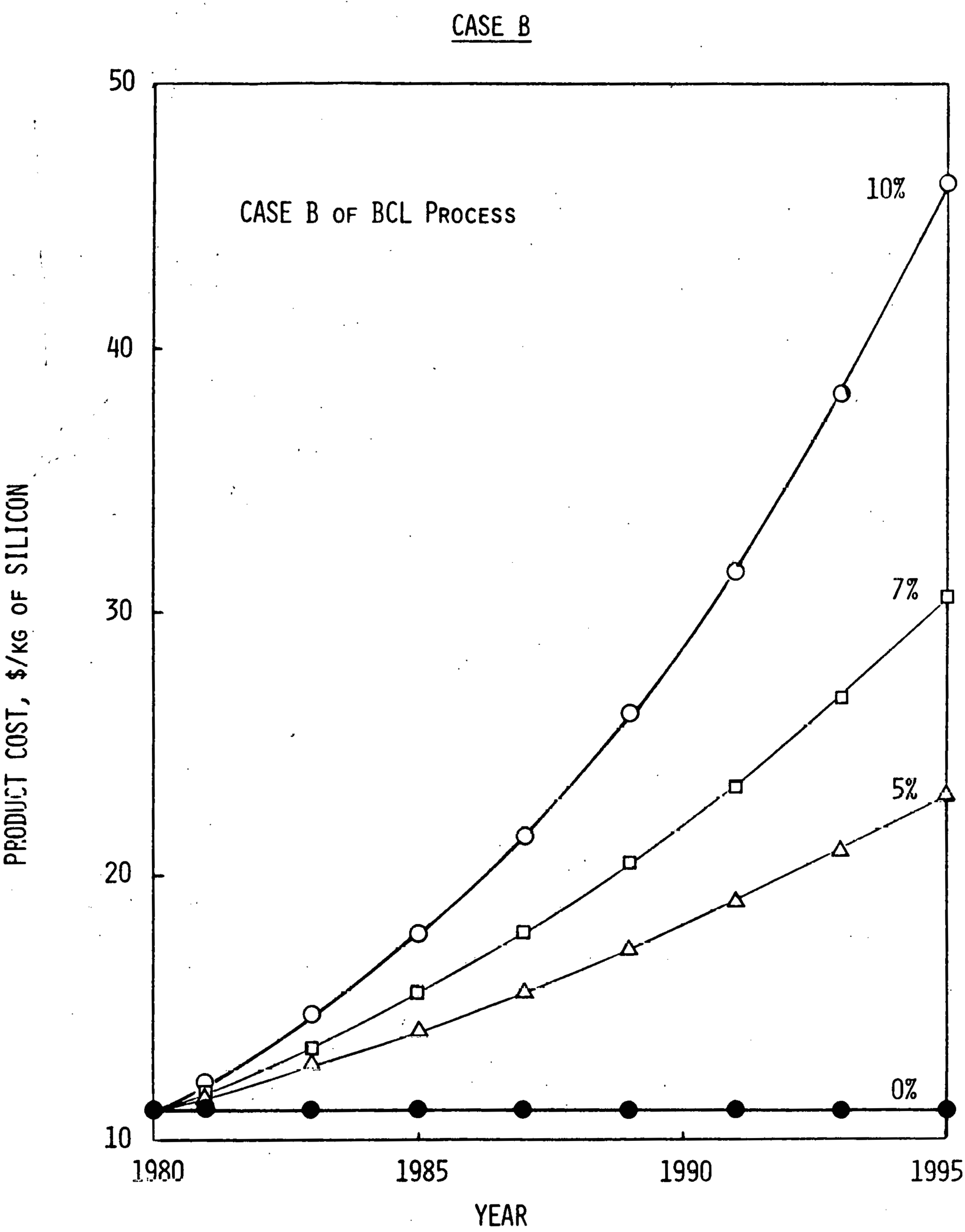


FIGURE IIIB-1.2 INFLATION EFFECT

IV. SUMMARY - CONCLUSION

The following summary-conclusions are made as a result of achievements during this reporting period.

1. Task 1

Analyses of process system properties were continued for important chemical materials involved in the several processes under consideration for semiconductor and solar cell grade silicon production. Major activities were devoted to physical, thermodynamic and transport property data for silicon. Property data are reported for vapor pressure, heat of vaporization, heat of sublimation, liquid heat capacity and solid heat capacity as a function of temperature to permit rapid usage in engineering.

2. Task 2

Chemical engineering analysis of the HSC process (Hemlock Semiconductor Corporation) for production of silicon was initiated. The process is based on hydrogen reduction of dichlorosilane (DCS) to produce the polysilicon. The chemical vapor deposition reaction for DCS is faster in rate than the conventional process route which utilizes trichlorosilane (TCS) as the silicon raw material. Status and progress are reported for primary activities of base case conditions (30%), reaction chemistry (25%) and process flow diagram (20%). Discussions with HSC and construction of a process flow diagram are in progress.

3. Task 3

Preliminary economic analysis of the BCL process (Case B) was completed. Cost analysis results are presented based on a preliminary process design of a plant to produce 1,000 metric tons/year of silicon. Fixed capital investment for the plant is $14.35 million (1980 dollars) and product cost without profit is 11.08 $/kg of silicon (1980 dollars). Cost sensitivity analysis indicate that the product cost is influenced most by plant investment and least by labor. For profitability, a sales price of 14 $/kg (1980 dollars) gives a 14% DCF rate of return on investment after taxes.

V. PLANS

Plans for the next reporting period are summarized below:

1. Task 1

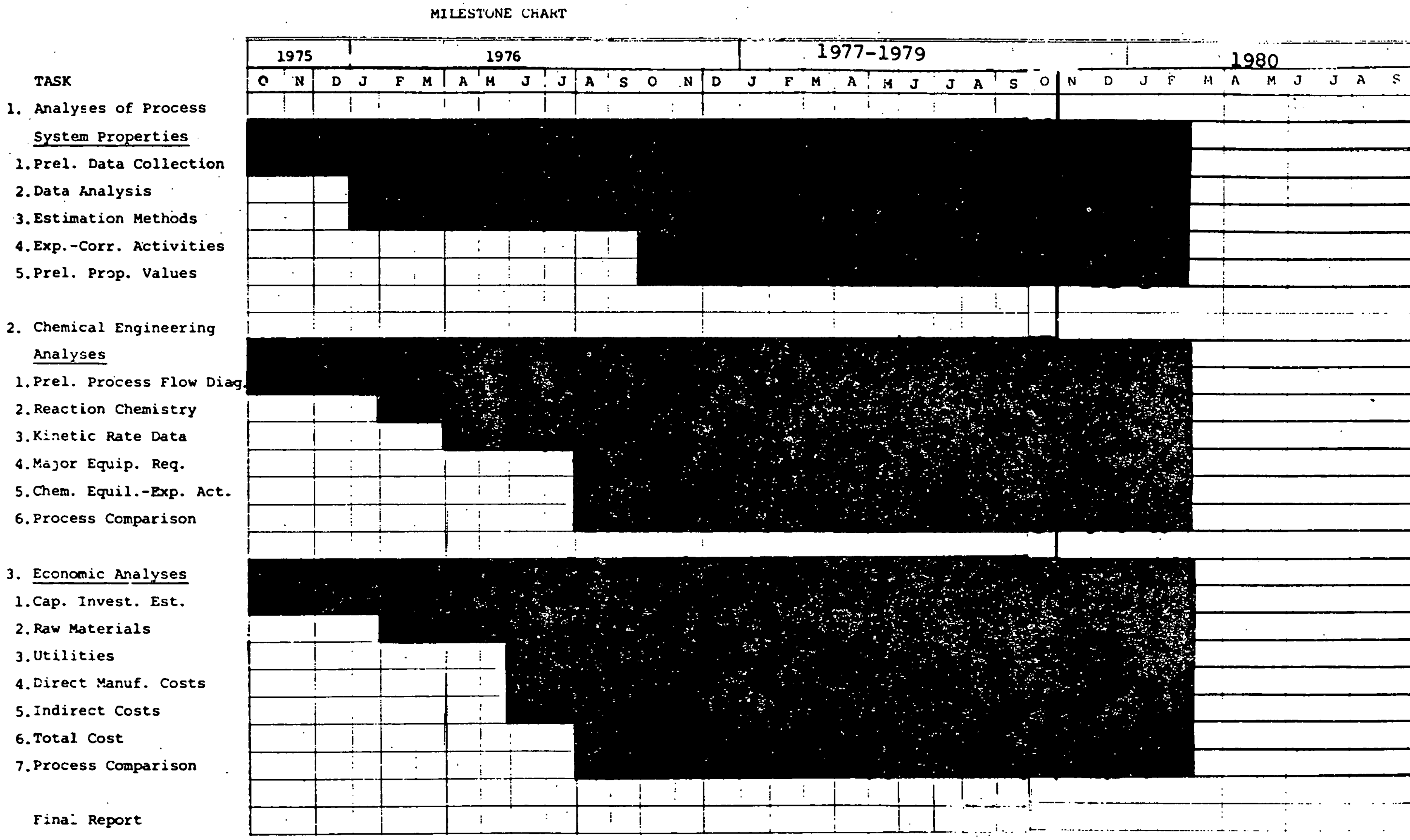
   Continue analysis of process system properties for chemical materials important to the production of silicon.

2. Task 2

   Continue chemical engineering analysis of processes under consideration for producing silicon.

3. Task 3

   Perform economic analysis of processes as results issue from chemical engineering analysis.



PROCESS FEASIBILITY STUDY IN
SUPPORT OF SILICON MATERIAL TASK I

JPL Contract No. 954343

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