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LSA LARGE AREA SILICON SHEET TASK CONTINUOUS
LIQUID FEED CZOCHRALSKI GROWTH

Quarterly Report No. 3, April—June 1978

By
George Fiegl

June 28, 1978

Work Performed Under Contract No. NAS-7-100-954886

Siltec Corporation
Menlo Park, California

U.S. Department of Energy

MASTER

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Solar Energy

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CONTINUOUS LIQUID FEED CZOCHRALSKI GROWTH

Siltec Document No. 0140-1-170

QUARTERLY REPORT #3

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The JPL Low-Cost Silicon Solar Array Project is sponsored by the U.S. Department of Energy and forms part of the Solar Photovoltaic Conversion Program to initiate a 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.

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ABSTRACT

Siltec Corporation's contract with JPL is directed towards the design and development of equipment and processes, to demonstrate continuous growth of crystals by the Czochralski method, suitable for producing single silicon crystals for use in solar cells. Continuous growth is defined as the growth of 100 Kg of single silicon crystal, 10 cm in diameter, from one container. Siltec's approach to meeting this goal is to develop a furnace with continuous liquid replenishment of the growth crucible, accomplished by a meltdown system and a liquid transfer mechanism, with associated automatic feedback controls.

During this reporting period, the design of the furnace elements was completed, and all parts are now in the fabrication stage. The electronic control console regulating the growth system and meltdown system, and the liquid transfer mechanism, was assembled.

An experiment was performed with a standard production furnace, to demonstrate controlled flow of molten silicon through a small I.D. tube by pressure differential.

Sections of the transfer tube system were evaluated, power requirements to balance heat losses determined, axial temperature profile in the tube, and radial temperature gradients in the heat pack were measured.

A mathematical model was made for the electromagnetic throttle valve to control flow of molten silicon through small I.D. tubes. Design parameters were derived from the model to build a working system for performance evaluation.

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1. INTRODUCTION

The overall purpose of this program, which began in October 1977, is the demonstration of continuous crystal growth by the Czochralski method. Continuous is defined as a throughput of silicon that produces 100 Kg of single crystal material, 10 cm in diameter, from one common container.

The program includes:

- . Design and fabrication of a basic CZ furnace with a second chamber to be used for melting of the polysilicon.
- . Design, development, and fabrication of the continuous liquid silicon feed system with automatic feedback controls.
- . Demonstration of continuous crystal growth, as defined above, with an after growth yield >80%.
- . Definition of process control variables for continuous Czochralski growth.
- . Theoretical analysis of silicon sheet growth to be considered during design and development of the furnace.

During the last quarter basic design work was completed and part of the effort was directed towards experimental investigation of critical phases of the program. These are:

- . Liquid Transfer System
- . Controlled Flow of Molten Silicon
- . Throttle Valve
- . Melt Level Control

2.0 RESULTS

2.1 FURNACE ELEMENTS

Design of basic furnace elements was completed and they are now in the fabrication stage. These consist of the symmetric frame, the dual chamber arrangement, and the associated top and bottom plates. Drive mechanisms for crucibles and seed carriage are also being fabricated. See drawings in Appendix I, pages 10 through 15.

2.2 ELECTRONIC CONTROLS

The electronic control console was assembled. The upper portion of this console incorporates controls for the growth system, while the lower portion of the panel regulates the melt down system and the liquid transfer mechanism. See Appendix I, Fig. 1.

2.3 MELT CONTAINERS - HOT ZONE

Liquid container elements and the hot zone for both the growth and the melt chamber were designed and are now in the manufacturing phase.

2.4 LIQUID TRANSFER SYSTEM

Portions of the transfer tube system were tested in a 5 feet long, 120 mm I.D. quartz tube with an argon atmosphere of 100 SCFH. The experimental set-up (Appendix I, Fig. 2) consists of a 7 inch section of the transfer tube. The clear fused quartz tube measures 8 mm I.D. and 25.4" O.D. In the first attempt to heat the tube section, a rigid graphite picket-type heater was used, which turned out to be too fragile for a production environment. Instead, a grafoil strip 0.5 inch wide and 0.015 mils thick that spiraled easily around the quartz tube, was investigated. The end turns of the grafoil heater were overlapped by molybdenum strips of equal width, forming rigid connections with the electrodes. A woven SiO₂ sleeve

Results

separated the heating element from the electrically conductive graphite felt, which in combination with the grafoil, formed the heat shield. See Appendix I, Fig. 3. The inside wall of the tube was brought to 1500°C by applying 55 volts, 21 Amps to the heater. The system reached thermal equilibrium at about 1100 watts. The axial temperature profile and the radial temperature gradient were measured. See Appendix, I, Fig. 5.

2.5 CONTROLLED FLOW OF MOLTEN SILICON

Tests to determine flow characteristics of molten silicon with P type impurities and a doping level of $5.6 \cdot 10^{14}$ A/ccm Si, were performed at 50°C above solidification temperature. A standard 10 Kg production furnace with a 10 inch diameter crucible was used for the experiment. Pressure conditions in the furnace were 2 inch to 3 inch of H₂O above atmospheric pressure. Using the gate valve, located in the throat of the furnace, a quartz source bottle, (Appendix I, Fig. 7), with an extended argon feed tube, was inserted and completely submerged into the melt. The I.D. of the flow tube was 4 mm to allow a flow of 250 mm³/sec at a velocity of 20 mm/sec, equivalent to the solidification rate of a 100 mm diameter crystal growing at 100 mm/hr. Owing to high surface tension of the molten silicon, the pressure differential created by the height difference between melt level and flow tube entrance, was not sufficient to allow filling of the bottle. Therefore, the pressure in the bottle had to be dropped 20 inches of H₂O below atmospheric pressure to achieve the appropriate pressure differential. After raising the source bottle enough to clear the exit of the flow tube

Results

(1/2 inch to 3/4 inch above melt level), argon was introduced through the main tube. The required pressure differential to achieve a flow of silicon for the given set-up was approximately 50 inches H₂O. Drops of molten silicon 1/4 inch diameter were formed at the exit of the flow tube initially, and a relatively steady stream of molten silicon could be sustained for about 10 seconds. Melt vibrations on the surface were of the order of 1/16 inch amplitude during the initial impact of the silicon stream. The test was successfully repeated three times. On the fourth attempt, the silicon solidified in the argon feed tube during the refill process. This particular section of the tube could not be heated enough to melt the silicon, and therefore the experiment had to be discontinued. The source bottle was full of molten silicon which had to be solidified to withdraw the set-up from the furnace, which made this system unusable for further experiments.

2.6 ELECTROMAGNETIC THROTTLE VALVE

A mathematical model for the throttle valve, to control flow of molten silicon through small I.D. tubing, was developed and a computer program was written to derive design parameters for the coil circuit. To obtain adequate control, 3000 dynes at a flow rate of 0.3 cc/sec must be achieved. This is to be accomplished by a two pole, three phase device. The coils will be made out of molybdenum wire since the system must be operable at 1500°C. The mathematical model and the computer program are presented in detail in a separate report. See Appendix I, pages 24 through 29.

Results

2.7 MELT LEVEL CONTROL

Portions of the automatic feedback control system to regulate the melt level in the growth chamber, have been developed. The electro optical sensing device for the melt level was tested on a slightly modified 860 C furnace. The system displays high linearity and allows control of the melt level to within .020 inch. During testing, it was found that an optical filter was needed to discriminate against the background radiation of the silicon melt. Suitable proportional control valves with a three mode controller for pressure differential regulation have been selected. The entire servo system is in its breadboard stage and will undergo extensive analysis for optimization.

3.0 CONCLUSIONS

- . Controlled flow of molten silicon through small I.D. tubing by pressure differential is feasible.
- . Strips of grafoil, spiralled around a quartz tube in a non-oxidizing atmosphere, readily form a very low cost heating element.
- . The electro-optical melt monitoring system shows high linearity, independence of melt surface vibrations, and an accuracy to within .020 inch.
- . The mathematical model for the electromagnetic throttle valve shows that, within reasonable design parameters, a force of 3000 dynes can be imposed on a stream of molten silicon.

4.0 PROJECTION OF ACTIVITIES

- 4.1 Completion of manufacturing of all furnace elements. This consists of the basic symmetric frame, the dual chamber arrangement (growth and melt chamber), the top and bottom plates and the crucible and seed drive mechanisms. Fabrication of the liquid container elements and the hot zones for the growth and melt chamber will also be completed.
- 4.2 Assembly of the entire system is planned in a specially reserved area measuring 15 feet by 20 feet. Functional testing of all mechanical subsystems will be performed. Electronic interface set-up with growth system, melt down system and liquid transfer mechanism will be installed. This will be by a total systems check out.
- 4.3 Two single crystals will be grown in the furnace by standard Czochralski method to demonstrate the growth system of the CLF furnace. At that time basic process parameters for the growth of 10 cm diameter crystals and 10 cm/hr growth velocity, will be determined.
- 4.4 A performance test is scheduled with an actual silicon transfer system, for the determination of temperature control along the entire transfer tube to define flow characteristics of the molten silicon in the tube, and to verify lifetimes of the various elements of the system.
- 4.5 Evaluation of the automatic feedback control system for constant melt level in the growth chamber consisting of the electro optical melt level sensing device, a three mode controller, a pressure differential transducer and the argon flow control valve for the meltdown chamber.

Projection of Activities

- 4.6 With the availability of actual data derived from the outlined activities above, Siltec will start to report a summary of characterization, design, and economic analysis data during the next quarter by reporting period.

APPENDIX I

SECTION A-A. HALF VIEW

SECTION B-D, HALE LINE
ROTATED 10° CW
TYPE, 0 PLACES

VIEW C-C, FINE LINE
ROTATED 20° SW. FROM
BEFORE PLACEMENT
OF ITEM 3, 1Y" & CLASS

- NO 155, UNLESS OTHERWISE SPECIFIED:
- 1. ALL WELD, TIG OR MIG
 - 2. NAME-PLATING OF ITEM + WILL BE REQUIRED.
 - 3. NOTED WALL CAVITIES TO BE LEAK-TIGHT.
MEDIUM LEAK CHECK TO 10" CC/SEC.
 - 4. PAINT OUTSIDE SURFACES,

5. NOTED AREAS TO BE PAINT-MAINTENED.

[illegible]

150 1 070 1VP

VIEW F
SCALE: FULL SIZE

- RECEIVED FBI MEMPHIS 4/11/68**
1. THE ABOVE-SUBJECT PHOTOGRAPHED ON APRIL 9, 1968, AND TO BE FILLED THE ABOVE-SUBJECT, AND THE ABOVE-SUBJECT OF MEMPHIS OF THE CIVIL.
2. ABOVE SUBJECT OF ABOVE SUBJECTS, THEN P. 75 TO BE FILLED THE CIVIL TO ONE OF THE ABOVE, THEN 100.
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8. ABOVE SUBJECT, THEN P. 75, ABOVE SUBJECTS ABOVE 100 TO ONE OF THE ABOVE, THEN 100.
9. ABOVE SUBJECT, THEN P. 75, ABOVE SUBJECTS ABOVE 100 TO ONE OF THE ABOVE, THEN 100.
10. ABOVE SUBJECT, THEN P. 75, ABOVE SUBJECTS ABOVE 100 TO ONE OF THE ABOVE, THEN 100.

[illegible]

SECTION AA

SECTION 6-B
FULL SIZE

[illegible]

Figure 1. The CFL control console.
Upper Portion: Controls for growing chamber.
Lower Portion: Controls for melt down chamber.

Figure 2. Set-up for testing a section of the liquid transfer tube. This consists of a 5 ft. long quartz tube, 120 mm I.D., closed at each end with an argon purge of 100 SCFH.

Figure 3. The heat shield pack consisting of five layers of 1/4 inch graphite felt and 0.015 mils grafoil.

Figure 4. Quartz tubes 8 mm I.D., 25.4 mm O.D. 11 inch and 7 inch sections. Grafoil heater strips with molybdenum connections visible. Both sections were at 1550°C for two hours.

Figure 5. Both electrode connections of the strip heater visible; transfer tube inside wall temperature 1560°C in middle of section.

Figure 6. Longitudinal and radial temperature distribution of the liquid transfer tube test section

Figure 7. Quartz bottle filled with molten silicon, nozzle 1/2 inch above melt level ready for pumping silicon.

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June 9, 1978

AN ELECTROMAGNETIC DEVICE FOR CONTROLLING
THE FLOW OF MOLTEN SILICON

The purpose of this report is to present the mathematical model developed to aid in the design of an electromagnet device to control the flow of molten silicon. The design goal is to develop a unit which will produce a force of at least 3003 dynes at a flow rate of .3 cc/second.

Electromagnetic pumps have been developed to pump coolants for atomic reactors and metal foundry casting systems. These devices operate on the same principle as conventional alternating current motors. A multiphase current source and an array of induction coils produce a traveling electromagnetic wave. The traveling electromagnetic wave produces a force on a current carrying conductor. In our case the conductor is a trough of molten silicon. The current in the melt may be produced by electrodes immersed in the melt or by induction by the same field that produces the force. Electrode type systems are more efficient than induction devices. As the electrodes are a source of contaminants, we have only considered the induction devices. Mechanical considerations have restricted the trough to a thick walled silicon dioxide tube approximately 25 cm long. The device will operate at 1500° C. As this temperature is above the Curie Temperature of known paramagnetic materials, magnetic pole pieces cannot be used. In order to produce a useable field in the conducting melt the diameter of the air wound field coils which must be as large as possible. The coils are to be wound from molybdenum wire. Molybdenum has a melting temperature of 2620° C.

To date, a three phase system has been considered. A two phase system

¹See Appendix #1

Electromagnetic Device
June 9, 1978
Page 2

may allow for larger coils in the specified length, which could result in a more efficient device.

To meet the preceding requirements and considerations, a mathematical model of a two pole three phase device was developed. A computer program of this model has been written to aid in studying the effect of varying some of the device's parameters.

A hardware model is being constructed to evaluate the assumptions made in the mathematical model. Tests using a graphite rod to simulate the silicon will be performed prior to actual tests with silicon in the oven.

The two pole three phase device consists of a silicon dioxide tube with coils forming a sandwich on both sides of the tube. Each phase uses four coils. Each phase's set of coils is staggered one-third the coil's diameter along the tube.

If the coils are excited from a three phase current source, a traveling magnetic field is generated which travels along the tube's axis, at a velocity, V, of:

$$1. \quad V = 2 \cdot D2 \cdot F$$

Where: V = Velocity of field

D2 = Individual coils diameter

F = Frequency of the drive current

The traveling field generates a voltage, E, across the conducting channel.

$$2. \quad E = d/dt(A1 \cdot G) = 2 \cdot D2 \cdot F \cdot A1 \cdot G$$

Where: E = Induced voltage

A1 = Area of the channel at right angles to the field

G = Magnetic field strength density across A1

²See Appendix #2

The generated voltage, E , causes an induced current, I_1 , to flow in the melt. The current circulates across the channel under the first coil or pole, then down one side of the tube and back across the channel under the next coil in the phase. The return current flows back along the tube to the first coil. The circulating current is equal to:

$$3. I_1 = E/R_1$$

Where: R_1 = Resistance of the current path

The operating frequency, F , is chosen so that inductance effects in the current loop may be neglected. The current elements flowing across the channel, flow 90° to the direction of the traveling field. The force on the fluid carrying the cross current is then:

$$4. F_1 = G \cdot L \cdot I_1$$

Where: L = The length of the current element
flowing 90° to the field direction

L is nearly equal to twice the channel diameter then:

$$5. F_1 = G \cdot 2 \cdot D \cdot I_1$$

The field along a center line produced by a flat circular coil of diameter, D_2 , is:

$$6. G = \frac{U \cdot (D_2/2)^2 \cdot 2 \cdot \pi \cdot N \cdot I}{2 \cdot ((D_2/2)^2 + B^2)^{3/2}}$$

Where: B = Distance from the plane of the coil

N = Number of turns

I = Driving current in amperes

U = Permeability in Henrys/Meter

The coil will be formed close to the outside of the tube. The approximate form will be circular.

If $D_2 \gg B$, then the field is nearly equal to the center line value at

Electricity Magnetism, Francis Weston Sears, Addison-Wesley Press, Inc., 1951, p. 272.

any position under the coil. Approximately 15% of the field from one pole is cancelled by the adjacent pole. The fields from the three phases are added by the factor square root of three. Adding these corrections to the field equation:

$$7. G = \frac{U \cdot (D_2/2)^2 \cdot 2 \cdot \pi \cdot N \cdot I}{((D_2/2)^2 + B^2)^{3/2}} \cdot 1.74$$

If we estimate that the area, A_1 , where the voltage is induced is:

$$8. A_1 = .75 \cdot I_2 \cdot D$$

Where: I_2 = length of the device

Also, the area of current flow, A_2 , is the geometric mean of the largest area and the smallest area then:

$$9. A_2 = 50R(.75 \cdot I_2 \cdot D \cdot P \cdot D \cdot A_2 / 8)$$

Where: $P = 3.14159$

and the length of the current path is:

$$10. I_1 = I_2 / 2$$

Then, the resistance of the current loop is:

$$11. R_1 = R \cdot I_1 / A_2$$

Where: R = Resistivity of the silicon in ohm/meters

Combining Equations 2, 3, 8 and 9 the induced current I_1 is:

$$12. I_1 = \frac{(2 \cdot D_2 \cdot F \cdot .75 \cdot I_2 \cdot D \cdot G) (50R(.75 \cdot I_2 \cdot D \cdot P \cdot D \cdot A_2 / 8))}{R \cdot I_2 / 2}$$

Mechanical considerations require that the maximum outside coil diameter equals $3/8 \cdot I_2$ and the inside diameter equals $I_2/4$. We will use the geometric mean of these dimensions for the coil diameter, D_2 .

$$13. D_2 = I_2 \cdot 50R(3/32) = .306 \cdot I_2$$

If we let B in Equation 5 equal the geometric mean of the center of the tube distance and the outside diameter to fluid distance plus one-half the winding depth then:

$$14. B = (\text{SQRT}((D1/2 \cdot (D1-D)/2) + N2 \cdot 1.2 \cdot D3/2))$$

Where: D1 = Outside tube diameter

D = Channel diameter

N2 = Number of winding layers per coil

D3 = Wire diameter

1.2 is a correction for the insulation thickness.

If we substitute in Equation 4; Equation 12 for I1, Equation 7 for G, Equation 8 for A1, note from Equation 13 that D2 = .306*12 and solve for the force, F1, as a function of D, L2, U, N3, I, F and R:

$$15. F1 = \frac{22.96 \cdot D \cdot U^2 / 2 \cdot 12 \cdot A1 / 2 \cdot (U \cdot N3 \cdot I) \cdot A2 \cdot F}{R \cdot (12 \cdot A2 + 10.6 \cdot (\text{SQRT}((D1 + (D1-D)) + (1.2 \cdot N2 \cdot D3) \cdot A2) \cdot A3)}$$

Note that the force, F1, is very sensitive to changes in channel diameter, D, and device length, L2.

In developing this model the major approximations were:

1. The coil configuration, Equation 6.
2. The voltage induced area, Equation 8.
3. The dimensions of the induced current channel, Equations 9 and 10.
4. Interaction between phases is negligible.

The attached computer program, FCSI, was used to optimize the device's variables.

Example of Two Different Configurations Run With FCSI

Channel Diameter	D =	.008 Meters	.020 Meters
Tube Outside Diameter	D1 =	.025 Meters	.035 Meters
Length of 12 Coil Array	L2 =	.25 Meters	.3 Meters
Wire Size	W =	20	0
Number of Winding layers	N2 =	4	4
Drive Current/Phase	I =	25 Amperes	75 Amperes
Frequency	F =	50*10^3 Hz	50*10^3 Hz

Force in Dynes	F1*10^5 =	2788 Dynes	3755 Dynes
Power Loss/Phase		4425 Watts	99.7 Watts
Turns/Coil	N3 =	117 Turns	14 Turns
Inductance Per Phase	L3 =	1.75E-3 Henrys	18.5E-6 Henrys

D. H. Patterson
D. H. Patterson

1. "applications possibles des champs electromagnetiques pour le transport, le traitement et le controle de la fonte et de l'acier liquides",

L. Cochet, R. Heirlyz, D. Jorre, R. Michaux

Contains theory of electrodeless pumps and describes applications. We are proceeding with a complete translation.

2. "Development and Testing of an Experimental and Electromagnetic Pump for Liquid Steel", T. S. Jones, S. Ramachandran, W. B. Yerrick, J. W. Gahan

Describes liquid steel pump with calculated and measured performances and data.

3. "Engineering Hydrodynamics", McGraw Hill, 1965

The book is mostly concerned with plasma accelerators.

4. "Some Considerations and Experiments on the Behavior of DC Conduction Electromagnetic Pumps", S. Kikuchi and K. Murakami

Deals with DC excited pumps. Portions of this well presented analysis may be extrapolated to our problem.

5. Patent 1 286 701 (German)

Shows metering method and general magnetic pump description.

6. Patent 2,707,718 (U.S.)

Shows general magnetic pump description.

7. Patent 3,980,287 (U.S.)

Shows unique flow technique for reduction of trough heating requirements.

8. Patent 3,754,634 (U.S.)

Shows general magnetic pump description.

9. "Hydrodynamics 1", Jul. Hartmann

DC excited pump with description of velocity distribution and interaction between flow and magnetic field.

```

10 REM* .....
20 REM* FCSI-PROGRAM FOR CALCULATING THE FORCE PRODUCED BY *
30 REM* A THREE PHASE INDUCTION FIELD ON A CHANNEL OF
40 REM* LIQUID SILICON. D.M.F. ASSOCIATES MAY 20, 1978 *
50 REM* .....
60 REM- THE VARIABLES ARE:
70 REM- A1 = THE AREA WHERE THE INDUCED VOLTAGE IS INDUCED
80 REM- A2 = THE CROSS SECTIONAL AREA OF THE CURRENT PATH
90 REM- B = CENTER OF FIELD COIL TO CENTER OF FLUID DISTANCE
100 REM- D = CHANNEL DIAMETER IN A CIRCULAR CHANNEL
110 REM- D1 = THE OUTSIDE DIAMETER OF THE TUBE
120 REM- D2 = SINGLE COIL DIAMETER
130 REM- D3 = WIRE DIAMETER
140 REM- D4 = OUTSIDE DIAMETER OF THE CIRCULAR TROUGH
150 REM- E = VOLTAGE INDUCED ACROSS THE FLUID'S CURRENT PATHS
160 REM- E1 =  $E/I = d/dl(G \cdot A1)$ 
170 REM- F = FREQUENCY OF THE DRIVING CURRENT
180 REM- F1 = THE FORCE IN NEWTONS
190 REM- G = MAGNETIC FIELD STRENGTH IN WEBERS/METER^2
200 REM- G1 =  $G/I$ 
210 REM- I = DRIVING CURRENT IN AMPERES
220 REM- I1 = INDUCED CURRENT IN LIQUID
230 REM- I2 =  $I1/I$  THE INDUCED CURRENT PER AMPERE OF DRIVE
240 REM- L = ELEMENT OF CURRENT PATH ACTED ON BY THE FORCE, F1
250 REM- L1 = LENGTH OF THE FLUID'S RESISTANCE PATH
260 REM- L2 = LENGTH OF THE 12 COIL ARRAY
270 REM- L3 = INDUCTANCE OF ONE PHASE IN HENRYS

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280 REM- N = NUMBER OF COIL SETS
290 REM- N1 = NUMBER OF TURNS OF WIRE PER COIL LAYER
300 REM- N2 = NUMBER OF LAYERS IN EACH COIL
310 REM- N3 = NUMBER OF TURNS PER COIL
320 REM- P = 3.14159
330 REM- R = RESISTIVITY OF THE SILICON MELT
340 REM- R = 3.33E-5 OHM-METERS
350 REM- R1 = RESISTANCE OF THE FLUID'S CURRENT PATH
360 REM- R2 = RESISTIVITY OF THE MOLYBDENUM WIRE AT 25 DEG. C.
370 REM- R2 = 4.7E-8 OHM-METERS
380 REM- R3 = RESISTANCE OF ONE PHASE (FOUR COILS)
390 REM- U = PERMEABILITY OF THE SILICON MELT
400 REM- U = 11.75E-7 HENRYS/METER
410 REM- W = WIRE SIZE
420 REM* * * * *
430 REM- F1 =  $G \cdot L \cdot I1$ , WHERE  $I1 = E/R1$  &  $E = d/dl(G \cdot A1) = d/dl(G1 \cdot I \cdot A1)$ 
440 LET P = 3.14159
450 LET R = 3.33E-5
460 LET R2 = 4.7E-8
470 LET U = 11.75E-7
480 INPUT "(ALL DIMENSIONS IN MKS) CHANNEL DIAMETER, D=",D
490 INPUT "TUBE OUTSIDE DIAMETER, D1=",D1
500 INPUT "LENGTH OF THE 12 COIL ARRAY, L2=",L2
510 LET D2 =  $SQR(3/8 \cdot L2 \cdot L2/4)$ : REM-THE MEAN COIL DIAMETER
520 INPUT "WIRE SIZE, W=",W
530 INPUT "NUMBER OF LAYERS OF WIRE ON THE COIL, N2=",N2

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540 INPUT "DRIVE CURRENT, I=", I
550 INPUT "DRIVE FREQUENCY, F=", F
560 GOSUB 600: REM-TO CALCULATE WIRE DATA
570 GOSUB 750: REM-CALCULATE THE MAGNETIC FIELD, G/I
580 LET A1 = .75*12*D: REM-THE AREA WHERE THE VOLTAGE IS INDUCED
590 LET E1 = 2*D2*F*A1*G1: REM-THE FIELD RATE IS 2*D2*F METERS/SEC
600 LET A2 = SQR(.75*12*D*F*D2/8): REM-THE GEOMETRIC MEAN OF THE
    CROSS SECTION OF CURRENT FLOW
610 LET L1 = D2: REM-THE MEAN CURRENT PATH LENGTH
620 LET R1 = R*L1/A2: REM-THE RESISTANCE OF THE SILICON'S CURRENT
    PATH
630 LET I1 = E1/R1: REM-I1 IS THE INDUCED CURRENT PER AMPERE
640 LET F1 = 2*D: REM-THE FORCE IS UPON THE CURRENT FLOWING ACROSS
    THE CHANNEL
650 LET F1 = 1*I1*G1*1A2: REM-FORCE IN NEWTONS
660 GOSUB 780: REM-PRINT OUT RESULTS
670 END
680 LET D3 = 8.23E-3/1.12 W: REM-CALCULATE WIRE DIAMETER
690 LET N1 = (12/8)/D3*.8: REM-THE NUMBER OF TURNS PER COIL LAYER
700 LET N3 = N1*N2: REM-NUMBER OF TURNS PER COIL
710 LET Y1 = P*D2*N3*2: REM-THE LENGTH OF WIRE PER PAIR OF COILS
720 LET R3 = 6*H2*Y1/(2*(2*P*D3)^2)/4: REM-RESISTANCE FOR A SET OF
    FOUR COILS AT 1500 DEG. C (*6) FOR A SET OF FOUR COILS
730 LET L3 = 1.86*(D2*N3)^2/(D2+2.67*N2*D3)*1E-6: REM-INDUCTANCE
    OF ONE PHASE IN HENRYS
740 RETURN
750 LET D = SQR(D1/2*(D1-D)/2)+(N2*1.2*E3)/2: REM-THE GEOMETRIC
    MEAN OF THE TUBE'S SURFACE TO THE FLUID + ONE-HALF THE COIL
    HEIGHT
760 LET G1 = .85*H*(D2/2)^2*H3/(2*((D2/2)^2+H2)^1.5)*SQR(3):
    REM-FIELD FROM THREE PHASES. EACH PHASE HAS .15% CANCELLATION

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770 RETURN
780 PRINT "          ", " * * * * "
790 PRINT "FORCE IN DYNES=", F1*1E5
800 PRINT "EFFICIENCY FACTOR=", 1*I1*G1/(R3+11*R1)
810 PRINT "RESISTANCE PER PHASE=", R3
820 PRINT "TURNS PER COIL=", N3
830 PRINT "WIRE NUMBER=      ", W
840 PRINT "POWER LOSS PER PHASE=", 1 2*(R3+11*R1)
850 PRINT "VOLT-AMPERES PER PHASE=", 2*P*F*L3*1A2
860 PRINT "LENGTH OF DEVICE=", L2
870 PRINT "          ", " * * * * "
875 PRINT "CHANGE VARIABLES AND RUN 560"
880 RETURN
890 FOR W = 0 TO 20 STEP 1: REM-SUBROUTINE TO OPTIMIZE PARAMETERS.
    CHANGE VARIABLES AND RUN 560
900 GOSUB 560
910 PRINT W, F1*1E5, 1A2*N3
920 NEXT W

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APPENDIX II

NEW TECHNOLOGY

No new technology was generated during the reporting period.

APPENDIX III

Summary of Characterization, Design, and Economic Analysis Data

There was no data generated during this quarter to analyze.

APPENDIX IV

Milestones

Labor Summary

Cost Summary

CALIFORNIA INSTITUTE OF TECHNOLOGY
Jet Propulsion Laboratory

LSSA LARGE AREA SILICON SHEET TASK
CONTINUOUS LIQUID FEED CZOCHRALSKI GROWTH

Contract No. 954886
Modification No. 1
DRL 61/DRD Line Item SC2
Siltec Doc. No. 0140-0203

PROGRAM PLAN

Revised: 6-8-78

Milestone Legend:

○ = Due Date
▼ = Start/Finish
● = Program Revision