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DOE/JPL/954355-80-1

LARGE AREA SILICON SHEET BY EFG

First Quarterly Report for January 1—March 31, 1980

MASTER

June 1, 1980

Work Performed Under Contract No. NAS-7-100-954355

Mobil Tyco Solar Energy Corporation
Waltham, Massachusetts

U.S. Department of Energy

Solar Energy

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LARGE AREA SILICON SHEET BY EFG

Program Manager: F.V. Wald

First Quarterly Report - Subcontract No. 954355

Covering Period: January 1, 1980 - March 31, 1980

June 1, 1980

"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

Operation of Furnace 3A in a multiple mode with three 10 cm cartridges and with melt replenishment has been demonstrated for the first time. Detailed characterization of the temperature field of the 10 cm cartridge has been started in order to assist in work on improving cartridge performance and in implementation of automatic controls.

Development of the 10 cm cartridge system in Furnace 17 has proceeded with efforts to improve high speed performance and to study means by which to improve ribbon quality. Reliable growth has been achieved up to speeds as high as 4.0 cm/min, and cell efficiencies of above 10% (AM1 and AR coated) have been demonstrated for this ribbon.

The study of ambient influences on growth conditions and quality has continued in Furnace 18 with additional growth with CO_2 present. The photovoltaic performance of ribbon grown with and without CO_2 has been investigated, and differences in light enhancement characteristics are observed as a function of the type of processing used, viz., CVD as compared to PH_3 .

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I. INTRODUCTION

The signal success of the five ribbon multiple run in May 1979, which produced from five cartridges 150 m of 5 cm wide ribbon with an average growth speed of ~3.5 cm/min at a machine duty cycle over 90%, has now clearly demonstrated that "cartridge type" multiple EFG machines can be considered "prototypical" for the development of the future production equipment with which to fabricate silicon ribbon base material at the low cost necessary to achieve the 1986 LSA project goals.

Upscaling of the cartridge to the ultimate 10 cm width which, at growth speeds below 5 cm/min, is considered necessary to achieve the final cost goals, is also well underway, along with the development of a viable automatic control system which at this point appears to be sufficiently advanced and also sufficiently inexpensive, to allow perhaps more than the originally projected ten ribbons to be under the control of a single machine operator.

The program has thus made great strides in arriving at a scalable production technology for multiple EFG ribbons, and it appears that in the coming year conclusive final design choices for a production unit will become possible.

Also, in the five ribbon multiple run, it was demonstrated that material from such units can indeed have reasonable electronic properties, since large area (~50 cm²) cells of ~9% efficiency could be prepared from silicon ribbon grown in that experiment.

Such efficiencies, although significant as a general demonstration that this type of equipment in principle can produce ribbon with acceptable electronic properties, are not considered sufficient to meet the LSA project goals for 1986.

Hence, very significant efforts in this program were directed toward the identification and study of mechanisms which could optimize or degrade the electronic properties of the ribbon during growth as well as

during processing into solar cells, and these studies will be further emphasized during the coming year.

So far as crystal growth is concerned, the work has focused on an examination of material quality changes arising from variations in die design, construction materials, thermal conditions and the furnace ambient.

Although we consider optimized die designs and thermal conditions to be worthy of further study, and of importance in particular as they allow us to influence the meniscus height during growth which appears to be a significant variable, it was the furnace ambient manipulation which has led to reproducible, unambiguous, and positive changes in growth system behavior and material quality, such that a definite breakout in solar cell performance over earlier baseline levels in these machines has been observed.

From these experiments, large area (50 cm^2) cells of 11.5% (AM1) efficiency have now resulted, and it is believed that optimization of the gas ambient in the furnace and particularly around the meniscus will lead to further efficiency increases. At this point, it is realized that the gas ambient, in particular with respect to carbon and/or oxygen containing species such as CO , CO_2 , and CH_4 , was perhaps the one most important unrecognized and uncontrolled parameter affecting growth and properties of EFG silicon ribbon prepared from carbon dies.

However, a distinct model linking ribbon properties and gas phase composition, flow, etc., must now be evolved and proven, and subsequently the results must be applied in appropriately designed machines which control and optimize the relevant parameters. Therefore, because of the apparent importance of the observations so far, we plan to devote a very significant effort to these questions in the year ahead.

Finally, it has become clear that solar cell fabrication sequences can have a significant influence on the material properties in the final cell through the high temperature processing now commonly associated with cell fabrication. It is also suggested that such influences can be both positive or negative, i.e., the diffusion length may decrease during processing, or, through such mechanisms as gettering, precipitation, or complexing, it may perhaps be made to increase.

In either case, the development of processing sequences which at least conserve, and hopefully could improve the initial minority carrier lifetime of imperfect materials, such as EFG ribbon, can conceivably have

a large influence on the final solar cell efficiency. These questions, therefore, will continue to be explored. However, at this point in time, multiple EFG ribbon technology appears to be extremely well placed toward actual achievement of the 1986 LSA program goals.

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II. HIGH SPEED GROWTH AND QUALITY STUDIES by J.P. Kalejs

A. Overview

Acceptable growth conditions in the speed range from 3.0 to 4.0 cm/min have been attained in the course of the development of the 10 cm wide ribbon cartridge system in Furnace 17 in this past quarter. More reliable growth has been achieved primarily as a result of improvements in the uniformity of the die-top temperature field. Experiments have been initiated to study the influence of variations in certain die design parameters on the maximum speed capability of the cartridge. Evaluation of the 10 cm wide ribbon for quality improvements has been continued in parallel with this development work. The study of ambient influences on growth conditions and quality has been started with a number of runs at reduced main zone flow rates and with CO₂ introduced into the interface environment. As a result, diffusion lengths for the 10 cm wide ribbon have been improved to levels above 30 μ m for growth at speeds of 3.8 to 4.0 cm/min. Cell efficiencies of above 10% (AM1 and AR coated) have now been demonstrated for 10 cm wide ribbon grown at speeds of the order of 4 cm/min.

Ambient studies in Furnace 18 have been concerned with obtaining additional ribbon grown with CO₂ present. The best solar cells to date, greater than 13% for small area cells (~ 6 cm²), have been obtained from ribbon grown under these conditions. A range of ambient conditions and some minor die design modifications have been explored to attempt to look for areas where material quality may be optimized. Preparations have been started to convert Furnace 18 over to growth of 10 cm wide ribbon.

B. Machine 17

Growth conditions for full-width steady-state growth of 10 cm wide ribbon have continued to improve as a result of additional experience

gained in cartridge operation. Better die-top isotherm uniformity, resulting from adjustment and minor redesign of cartridge components, has allowed growth of thinner ribbon (~ 0.025 cm) with good reproducibility. Installation of a new 10 cm puller has helped further. The experimental details are summarized in Table I. Excellent growth conditions now have been attained for growth speeds up to 4.0 cm/min.

The designs of all cartridge components except the die were fixed, starting with run 17-075. Several modifications in die design have been evaluated with respect to their usefulness in improving the maximum growth speeds and the ribbon quality. Among the parameters investigated were the capillary thickness, displacement magnitude and bulb configuration. In addition, a two-piece die used in the multiple furnace cartridge was evaluated in run 17-086 in conjunction with the operation of one of these cartridges in Furnace 17. In general, large differences in growth performance or in material quality that favor one particular design have not been observed on the basis of the experiments carried out to date, and this work is continuing.

Two aspects of the ambient influence on quality have been examined. First, the main zone purge rate has been gradually reduced in the course of the experiments, and changes in growth conditions and SPV diffusion lengths monitored. Second, a mixture of 1% CO_2 in argon has been introduced to the cartridge through quartz gas tubes extending into the corners of the cartridge (runs 17-084 and -085). Growth with reduced main zone purge rates (6 to 7 ℓ/min) has appeared to be responsible for increased diffusion lengths, as seen in Table I. Similar results were obtained with the CO_2 . Except in one run, 17-089, in which the purge rate used was so low that growth conditions deteriorated noticeably, average run diffusion lengths over this period have increased to above 30 μm from previous baseline levels of 15 to 30 μm established during growth at higher purge rates. The initial attempts to use CO_2 have not resulted in demonstrable increases in diffusion length above those typical of reduced purge rate conditions. Ribbon surface film appearance is generally indistinguishable in these two cases, indicating that the CO_2 probably does not reach the interface before decomposing to CO. Different geometrical configurations for gas inlets will be tried out in the near future to look for more reliable means by which to supply the gas to the interface.

Table I. Furnace 17 Run and Ribbon Data. All Runs Utilized a 10 cm Cartridge with a Cold Shoe, Except where Noted Otherwise.

Run No.	Speed Range (cm/min)	Furnace Gas Flows (ℓ /min)		Die Design Slot/Displacement (cm)	L_D (μ m)	Comments
		Main Zone	Cartridge			
17-071	2.5 - 2.6	13	1	0.025/0.008	23	Afterheater power problems limit growth.
17-072	3.0 - 3.5	13	1	0.025/0.008	30	First run with new 10 cm puller.
17-073	3.0 - 3.5	13	1	0.025/0.008	-	Growth limited by blockage in growth slot.
17-074	3.0 - 3.5	11	1	0.025/0.008	28	Modified face heater tested with satisfactory results.
17-075	3.0 - 3.6	11	1	0.025/0.008	19	Repeat of 17-074.
17-076	3.5	10	1	0.025/0	24	Crucible emptied without any freezes for entire run.
17-077	2.4 - 3.5	9.5	1	two-piece	-	No full-width growth possible due to thermal imbalances at ribbon edges.
17-078	3.0 - 3.5	9	1	0.025/0.012	22	Growth of thin (0.015 to 0.020 cm) ribbon for quality evaluation.
17-079	3.4 - 3.8	8	1	0.025/0.012	26	Repeat of 17-078.
17-080	3.0 - 3.5	6.5	0.5	two-piece	21	Cartridge from multiple furnace evaluated. Reasonable growth conditions.

Table I (continued)...

Run No.	Speed Range (cm/min)	Furnace Gas Flows (ℓ /min)		Die Design Slot/Displacement (cm)	L_D (μ m)	Comments
		Main Zone	Cartridge			
17-081	3.5 - 4.0	6.5	1	0.025/0.012	26	Change to different die with modified saw cuts and smaller bulb drill hole diameter.
17-082	3.5 - 4.0	6	1	0.025/0.012	14	Repeat of run 17-081.
17-083	4.0 - 4.5	6	1	0.040/0.012	24	Modified die with trimmed die ends introduced.
17-084	3.8	6	1% CO_2 0.5 - 1.0	0.025/0.012	32 (32) *	First use of CO_2 with cold shoes.
17-085	3.8	9	1% CO_2 0.5 - 1	0.025/0.012	33 (31) *	Repeat of run 17-085.
17-086	1.8 - 1.9	6.5 - 9	1	0.025/0.012	39	First trial of cartridge without cold shoes. Poor growth conditions.
17-087	3.8 - 4.0	6.5	1	0.040/0.012	33	Growth at lower main zone purge rates.
17-088	1.9 - 3.8	6	1	0.040/0.012	33	Growth speed effect on quality examined.
17-089	3.0	5	1	0.040/0.012	26	Reduced main zone purge rates led to growth problems with heavy film, cracked ribbon.
17-090	3.7	5.5 - 6.5	1	0.040/0.012	36	Repeat of 17-089.

*First number is for ribbon grown with CO_2 off; the value in parentheses is for CO_2 on.

C. Machine 18 (JPL No. 1)

The main emphasis in the ambient experiments in Furnace 18 has been on growth of 5 cm wide ribbon with CO_2 in order to provide more material for the purpose of characterization and solar cell fabrication. Several combinations of CO_2 concentration and main zone purge rate have been tried to look for areas in which material quality may be optimized. In this respect, the die capillary channel width has also been included as a parameter. Ribbon has been grown from both 5 cm wide and 0.8 cm wide central channel dies. This ribbon will be examined to see if responses in material quality are related to the change in this die design parameter. A summary of the experimental results is given in Table II. Additional details are presented in the discussion on characterization.

Examination of the maximum speed growth capabilities of a cartridge without a cold shoe was started in runs 18-202 to 18-204. This direction of investigation was initiated because attempts to date to reproduce quality improvements by ambient manipulation with cold shoes present have been unsuccessful. It is suspected that the ambient gas changes achieved at reduced main zone purge rates or with CO_2 are not effective in the presence of the cold shoes, either because the latter act as a gettering site for a condensable gas such as SiO , hence reducing its partial pressure in the meniscus region, or that gas flow patterns are unfavorably altered when the cold shoes are inserted. The experiments to investigate the high speed capabilities of the cartridge without a cold shoe were started in order to attempt to grow ribbon for quality evaluation at speeds intermediate to those available with the standard cartridge either with or without the cold shoes in place. For this purpose, a modified linear cooling plate/afterheater design was used, where the afterheater consists simply of two graphite rods entirely enclosed within the linear cooling plate. This arrangement greatly reduces the heating of the die-top shield by the afterheater in comparison to the regular configuration, where the afterheater can radiate directly onto the shield. Speeds of up to 3 cm/min were achieved with this setup. However, growth conditions were generally poor in the three runs attempted because of other design shortcomings, and so experiments were not continued. This line of investigation — to modify the cartridge without the cold shoe for higher speed growth — will be pursued in the future in the 10 cm cartridge.

The influence of the main zone temperature on growth conditions and ribbon quality was investigated in run 18-205. The main zone was deliberately cycled between two temperatures and ribbon was grown at each.

Table II. Furnace 18 (JPL No. 1) Run and Ribbon Data. The Runs Utilized a Cartridge Without a Cold Shoe, Except as Noted.

Run No.	Speed Range (cm/min)	Length (m)	Comments
18-191	2.0 - 2.2	4.8	Repeat of 18-172 with CO ₂ introduced into cartridge.
18-192	2.2	0.5	Growth attempts with quartz crucible unsuccessful due to crucible failure and silicon flood to main zone.
18-193	2.0	0.5	Growth abbreviated due to die failure.
18-194	1.5 - 2.1	4.5	Repeat of growth with CO ₂ introduced into cartridge. Poor growth conditions due to thermal imbalances.
18-195	1.5 - 2.0	3.6	Repeat of growth with CO ₂ in cartridge ambient. Narrow channel (0.8 cm) die.
18-196	2.0 - 2.2	3.8	Repeat of growth with CO ₂ and wide channel die.
18-197	1.9 - 2.2	2.6	Repeat of 18-195 with narrow channel die.
18-198	3.5 - 4.0	5.1	Growth with cold shoe at reduced main zone purge rates.
18-199	1.9 - 2.2	3.0	Repeat of growth with CO ₂ and wide channel die.
18-200	2.0 - 2.2	2.5	Repeat of growth with CO ₂ and wide channel die.
18-201	2.0 - 2.2	2.3	Growth with CO ₂ and reduced main zone purge rates.
18-202	2.4 - 3.0	2.5	Test of modified linear cooling plate and afterheater design for higher speed growth without cold shoes. Poor growth conditions due to malfunction in afterheater.
18-203	2.0 - 2.5	3.2	Repeat of 18-202. Poor growth conditions due to broken seed and die top silicon spill and malfunctioning afterheater.
18-204	2.0 - 2.2	1.7	Repeat of 18-202. Poor growth conditions. Flood to main zone terminated growth.
18-205	2.0 - 2.2	4.3	Repeat of 18-199 with CO ₂ in ambient to extend data baseline. Operation at several crucible melt temperatures.

The bulk melt temperature in the two cases was estimated to be 1450 and 1575°C. No obvious differences in ribbon appearance or SiC particle density were evident. The level of CO₂ in the gas jets was kept constant throughout the cycling. Growth became noticeably more difficult for temperatures in the range of the upper value given above. Both ramping transients and ribbon edge stability were affected, and the highest temperature used was chosen because growth over reasonable time periods could be sustained in spite of increasing ribbon edge instabilities.

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III. MULTIPLE GROWTH AND AUTOMATIC CONTROLS by B.H. Mackintosh

A. Overview

The operation of Furnace 3A with three 10 cm growth stations was demonstrated for the first time during this quarter. Performance of the individual growth stations was similar to that seen in single-ribbon runs made in this furnace in the fourth-quarter of 1979, i.e., growth rates around 3.0 cm/minute, and relatively poor stability. These characteristics yielded a machine duty rate far below that demonstrated in multiple (five 5 cm ribbon) operation of the furnace in May 1979. The low throughput demonstrated in these recent runs reflects both the increased stringency of design requirements for growth of the wider ribbon, and the smaller amount of developmental time invested in the 10 cm cartridge than the 5 cm system had undergone by the end of that phase of the contract.

Based partly on the outcome of these runs, a detailed plan was established for improvement of the cartridge and implementation of automatic growth controls to allow the final multiple growth demonstration goals to be met by the end of July 1980. As a first step in systematically optimizing the 10 cm cartridge, numerous measurements of temperatures and heat flows in various components were taken in March.

B. Multiple Demonstration Runs - Preparation

In January, the remaining equipment required to operate the furnace in a three-ribbon mode was assembled, tested, and installed on the machine. A batch of replacement main-furnace heating elements was received, and a series of non-growth heatup cycles was performed to test the temperature uniformity along the length of the hot zone produced by various combinations of new and old center and end heating elements.

One single-cartridge growth run was made to check the operation of the newly-designed 10 cm ribbon puller, and a die with a modified end-

bulb dimension. Two three-ribbon runs of about one day's duration were then carried out. Deliberate differences between components used in these runs were minor, as described below.

Run 215 utilized three newly-constructed cartridges, all with dies having .038 cm capillaries and .010 cm displacements, graphite die-top shields, and with ribbon slot gas locks in place. In run 216, the same cartridge was used in position No. 1 as in 215, but fitted with a .051 cm capillary displaced die. Position No. 2 was occupied by the first-built cartridge (in use since June 1979) with a .038 cm capillary displaced die. In position No. 3, the cartridge normally operated in Furnace 17 was inserted, also with a .038 cm capillary die. The ribbon slot gas locks were not in place on any of the cartridges.

C. Multiple Demonstration Runs - Outcome

The throughput performance of the machine in these runs is depicted by Tables III and IV.

D. Discussion

In general, the cartridges performed similarly to one another and at the performance levels seen in those runs in the fourth quarter in which ribbon was successfully grown. We believe that the figure for "length of ribbon grown" in Table III is in error for cartridge No. 2 due to misplacing or breakage of some of the ribbons. Average growth rates in the tables are computed by dividing length of ribbon accounted for after the run by the sum of durations of the growth periods. The run notes show a typical speed dial setting of 3.1 cm/min for this cartridge during steady-state growth, similar to that of the other stations.

Run 216 was foreshortened by the occurrence of a silicon flood. For the first time in nine instances of its use, the connecting tube between two graphite crucibles leaked, due to an imprecisely fitted joint. Cartridge No. 3 in run 216 exhibited a misalignment between the puller and the die, making seeding particularly difficult, and causing the ribbon to be grown with discrete twists. These problems aside, the tabulated data and run notes show that the throughput performance of the 10 cm system is limited at present by two generic faults, namely a poor die-top thermal environment, and tendency of the cartridge to induce stresses which cause breakage of seed ribbons.

The low growth rate, difficulty in spreading from less than full width, and short duration of full-width growth during unattended growth

Table III. Run 16-215.

Run duration (minutes): 572
Time percentage of simultaneous three-ribbon growth: 12.7

	Cartridge No. 1	Cartridge No. 2	Cartridge No. 3	Total
Length of ribbon growth (m)	6.64	4.08*	10.75	21.47
Length $\geq$ 10 cm wide ribbon (m)	3.89	1.14	7.01	12.04
% $\geq$ 10 cm wide ribbon	58.6	27.9	65.2	56.1
Growth time total (min)	221	201	419	
Longest growth time (min)	92	128	273	
Number of freezes	11	5	6	
Average growth rate (cm/min)	3.00	2.03*	2.56	
% of run time operating	38.6	35.1	73.3	

*See discussion in text.

Theoretical possible length of ribbon (572 min x 2.8 cm/min x 3) = 48.05 m

Duty rate based on total length actually growth = $\frac{21.47 \text{ m}}{48.05 \text{ m}} = .447$

Duty rate based on total length of 10 cm wide ribbon = $\frac{12.04 \text{ m}}{48.05 \text{ m}} = .251$

Table IV. Run 16-216.

Run duration (minutes): 360
 Time percentage of simultaneous three-ribbon growth: 8.0

	Cartridge No. 1	Cartridge No. 2	Cartridge No. 3	Total
Length of ribbon grown (m)	4.40	4.45	2.71	11.56
Length of ≥ 10 cm wide ribbon (m)	2.38	0	0.38	2.76
% of ≥ 10 cm wide ribbon	54.1	0	14.1	23.9
Growth time total (min)	147	140	92	
Longest growth time (min)	51	33	32	
Number of freezes	8	8	6	
Average growth rate (cm/min)	2.99	3.18	2.95	
% of run time operating	40.8	38.9	25.6	

Theoretical possible length of ribbon (360 min x 3.0 cm/min x 3) = 32.40 m

Duty rate based on total length actually grown = $\frac{11.56 \text{ m}}{32.40 \text{ m}} = .357$

Duty rate based on total length of 10 cm wide ribbon = $\frac{2.56 \text{ m}}{32.40 \text{ m}} = .079$

segments (poor stability) are symptoms of a die-top thermal environment which is generally too hot, and at present is believed to be hotter at the die ends than at the center. This is the opposite of the condition desired for end stability and high growth rate in EFG. There is little observed tendency in the cartridge, when operated in this furnace, for the ribbon edges to grow onto, or remain on the die end bulbs. In the absence of a relatively large radius of curvature around the ribbon's end, meniscus height at this location must be so small that the growth is susceptible to freezes when small temperature or pull rate fluctuations occur, or when silicon carbide particles are picked up.

The replacement of the molybdenum die-top shield with one of graphite, discussed in the Fourth Quarterly Report, measurably reduced the growth rate potential of the cartridge. An effort to provide a colder die-top environment by increasing the area of the cold shoe faces in three runs made in October and November was inconclusive but seemed to cause higher stress and greater tendency for seed ribbons to break when inserted into the region of the cold shoes.

With the thinner cold shoes in place, as was the case in these runs, the majority of seed breakage incidents were caused by the abrupt transition from room temperature to $\sim 600^{\circ}\text{C}$ undergone by seed ribbons upon insertion into the top of the cartridge. A large part, 40% or more, of the loss in duty rate during runs 215 and 216 may be ascribed to difficulties with ribbon breakage. The principal means of preventing ribbon breakage are the use of thick seed ribbons, and slow ribbon insertion and withdrawal. Full-width ribbon grown by this system is generally too thin to serve safely as seed material and, conversely, the thick ($> .035$ cm) ribbons which are suitable are generally of less than full width. The operation of spreading ribbon in the cartridge as it is now configured is slow and requires constant operator attention. The slow, careful insertion of seed ribbons, i.e., at 3 cm per minute, is also time-consuming.

When small pieces of silicon do break off the seed ribbon, the remedy is to melt them into the die. In this procedure, the rate of melting must be carefully controlled so that silicon does not run down the outside of the die or bridge to the die-top shield. Finally, when large pieces break off and lodge in the cartridge, the puller must be unbolted and raised so that the material can be pulled out with the molybdenum wires or strips of silicon. This procedure compromises the system's cleanliness.

Although the impact of the ribbon breakage problem was severe in these runs, it manifested itself only during the growth startup process.

Ribbon produced by this system, once grown out, has a negligible level of residual stress. Hence, the afterheater is serving its principal function well. We are hesitant to change its design at the present time to attempt to lessen the stress it induces in seed ribbons. Instead, we are assuming that the current seed-breakage problems will become less important as long, stable growth runs become possible. We expect the improvement of the die-top thermal environment and the implementation of closed-loop optical control over the process to result in continuous runs of several days' duration.

E. Comparison of Cartridge Performance in Furnaces 3A and 17

The establishment of routine growth of 10 cm ribbon in Furnace 17 during the previous quarter provided some guidance for choice of the die heater configuration in the cartridges used in Furnace 3A, and has also raised questions about the effects of differences between the two furnaces on performance of the cartridges. The principal differences observed to date are in growth rate, thickness (related to rate), surface film formation, and silicon carbide particle density. The faster growth (3.6 cm/min routinely) in Furnace 17 is of particular interest at this time, in light of the contract goals for multiple growth at 3.5 cm/minute by the end of 1979 (not achieved) and 4.5 cm/minute by July 31, 1980. Two direct cartridge transfers were made in February between the two furnaces. In the first of these, mentioned above, the cartridge normally run in Furnace 17 was used in Furnace 3A in run 216, where it produced ribbon at an average of 2.95 cm/minute, at a very low duty rate.

The second exchange of cartridges between the two furnaces produced more information. One of the Furnace 3A cartridges was outfitted with three extra thermocouples and was operated in the two furnaces on consecutive days. Furnace 3A was run with all three cartridges in place and powered (but two without dies installed) to simulate the thermal conditions of multiple operation. (This has been adopted as standard practice for developmental runs.) A range of growth rates from 2.5 to 3.4 cm/minute was explored in Furnace 3A; above this upper limit, the die ends would freeze. Growth was stable at 3.5 cm/minute in Furnace 17, but the experiment ended before the rate could be raised further, when the afterheater thermocouple failed. This experiment confirmed that ribbon can be pulled at a somewhat higher rate in Furnace 17 than 3A, using the same

actual components. The three extra thermocouples present in the cartridge indicate the reason for this difference. Figure 1(a) shows the locations of these thermocouples in the general region of the die. The temperatures indicated during two stages of each run were as shown in Table V. The temperatures in these locations are different in the two furnaces because of the different thicknesses and placement of the hot zone insulation, with Furnace 3A being the better insulated of the two. It is a basic principle of design of the multiple ribbon furnace that the thermal environment of the ribbon is determined primarily by the elements within the cartridge, and that growth performance is relatively insensitive to thermal fields external to the cartridge. This experiment reveals the degree to which growth performance (e.g., maximum pull rate) is sensitive to these external temperatures, mainly because the inner surfaces of the cartridge walls form part of the radiative environment of the growing ribbon. This sensitivity could be reduced by decreasing the vertical distance between the die top and cold shoe, subject to the constraint that the growth interface must be observed in order to control the process.

The temperature measurements shown for the cold shoes in Table V are estimated to be 200 to 300 degrees higher than the actual temperatures due to the limited depth of the thermocouple cavity it is possible to make in these parts, and the extreme temperature difference between the cold shoes and their surroundings. Additional temperature measurements are discussed later in this report.

Part of the difference in typical growth rates of the same or similar cartridges operated in Furnaces 3A and 17 has to do with the tradeoff between rate and stability. Ribbon can consistently be grown in Furnace 17 close to the limiting rate because of full-time operator control, which is facilitated on that machine by the anamorphic video system.

F. Plan for Development of 10 cm Multiple Ribbon Technology, March Through July 1980

In accordance with the contract goals to demonstrate multiple growth of 10 cm ribbon at 4.5 cm/minute, under partially automatic control by July 31, 1980, the following sequence of activities is planned:

1. Cartridge Characterization

The baseline cartridge currently in use will be subjected to a series of temperature, gas flow, and heat flow measurements to provide

Fig. 1a. Thermocouple locations refer to Table V.

Fig. 1b. Configurations of furnace hot zones: Machine 17, right half; Machine 3A, left half.

Table V. Temperatures of Cartridge Components:
Comparison Between Furnaces 3A and 17.

Furnace No.	3A		17	
Run No.	217	217	080	080
Growth Status	seeding	growing	seeding	growing
Measurement Location*				
Cold Shoe (D1)	750°C	730°C	665°C	635°C
Left Side Wall (F1)	1250°C	1225°C	1075°C	1130°C
Right Side Wall (F2)	1300°C	1275°C	1060°C	1115°C

*These locations are indicated on Figure 1.

supporting data for the variety of developmental activities it is to undergo. Some examples of these measurements and the uses to which they may be put are:

a. Temperatures of side walls, floor, face walls and die shield. Accurate determination of these temperatures is essential to the study of the die-top thermal environment. These measurements will also permit a more precise determination to be made of relative locations and fits of these components at operating temperature. Finally, knowledge of temperatures in the cartridge will help determine where reactive gases should be introduced, and help to predict the rates of their reaction with various components.

b. Relationship between temperature distribution in the die and heating element power. These data will be useful for determination of the gains of closed-loop control systems, and choice of optimum heating element configuration.

c. Temperature distribution in, and heat transfer to, the cold shoe. These measurements are preliminary to the "cold shoe optimization" study, described below.

d. Temperatures of heater feedbars. The molybdenum rods that feed current to the four heating elements in the cartridge are the components with the shortest life and may, in production operation, stand out as a major consumable-cost item. Design refinements will be considered for these bars, based on these measurements.

e. Temperature profile experienced by ribbon in the linear cooling plates. These measurements will help to clarify the cause of the ribbon breakage problem, discussed above.

f. Flow characteristics of cartridge gas passages and orifices. Measurements of pressure drop vs. flow rate through the various cartridge gas passages will be useful for controlling the composition and flow direction of gases in the cartridge, especially in the possible case of the deliberate introduction of oxygen-bearing gases to improve the ribbon's photovoltaic performance.

A number of these cartridge characterization measurements were made in March and are reported below.

2. Cold Shoe Optimization

We will study the function of the cold shoes and, primarily by empirical means, modify their design to achieve higher growth rate and better stability. In particular, the distribution of temperature and surface area across the width of the cold shoes will be considered. It is generally observed with cold shoes of the current design that the limiting growth rate is achieved when silicon freezes in the ends of the die, i.e., the meniscus gradient becomes zero there. Cold shoes which provide relatively greater heat removal at these locations will be evaluated. The first cold shoe set of this type was fabricated during March and is ready for testing.

3. Automatic Growth Controls

Closed loop control of ribbon edge positions and central meniscus height will be implemented. Appropriate measurements will be made on the growth system to permit design of the controller transfer functions. The video analysis electronics for this overall system have been fully developed and are ready for use. Some minor modifications to the existing control electronics on the furnace will be necessary to permit connection of the video-based controller. We intend to have fully automatic controls on at least one station of the furnace during multiple growth demonstration runs in July.

4. Verification of Reactive-Ambient Effects Developed in Furnace 17 and/or Furnace 18

Some run time is set aside in the schedule of Furnace 3A for verification, in single-cartridge operation, of a method of quality improvement through manipulation of cartridge gases which is developed in one of the other furnaces.

5. Multiple 10 cm Growth Demonstration

The final goals for this phase of the contract are:

Run Length:	8 hours
Growth Rate:	4.5 cm/minute
Machine Duty Rate:	$\geq 85\%$
Solar Cell Efficiency:	10.2% average
Automatic Controls:	operational

Scheduled date for completion of this phase of the project is July 31, 1980.

G. Cartridge Temperature Measurements

Operation of the furnace in March was devoted to the taking of temperature measurements in both non-growth operation of the cartridge, and while pulling ribbon. Table VI lists the measurements taken and the figures which illustrate the locations of these measurements.

These measurements, and others that will be made in the near future, are intended to provide a general body of data on the 10 cm cartridge in its present form, to support the engineering development of its various aspects.

Table VI. Cartridge Characterization Measurements.

Figure and Table Nos.	Reference		Measurement
	Figure No.	Location	
Figure 2	3	A1 - A11	Vertical profile in die; no silicon.
Figure 4	3	A1 - A11	Temperature in die vs. left end heater current; 11 places across die; no silicon.
Figure 5	3	B1, C1, C2, C3	Temperatures of cartridge components vs. left end heater current.
Figure 6	3	B1, B2, C1, C2	Temperatures of cartridge components vs. face heater setpoint.
Figure 7	3	C2	Temperature of die top shield vs. after-heater setpoint.
Figure 8	9		Temperatures in cartridge components vs. melt replenisher setting.
Figure 10	11		Temperature profile of linear cooling plates.
Table VII	3	D1, D2, D3	Cold shoe temperature measurements.
Table VIII	3	E1, E2, E3	Heater feed bar temperature measurements.

Fig. 2. Vertical temperature profile in die tip. Average of measurements at locations A1 to A11 (refer to Fig. 3). No silicon in die.

Fig. 3. Thermocouple locations for "cartridge characterization" measurements.

Fig. 4. Temperature in die tip vs. current in left end heater. Thermocouple .25 cm deep in locations A1 to A11 (refer to Fig. 3). Other controls at settings typical for growth.

Fig. 5. Temperature in cartridge components vs. current in left end heater. Other controls at settings typical for growth. For locations, refer to Fig. 3.

Fig. 6. Temperature of cartridge components vs. face heater setpoint.

Fig. 7. Temperature of die top shield vs. afterheater setpoint.

Fig. 8. Temperatures in cartridge components vs. melt feeder temperature setting. Refer to Fig. 9 for locations.

—○—○—○— with crucible and silicon
 - - - - - without crucible and silicon

Fig. 9. Thermocouple locations for Fig. 8.

Fig. 10. Vertical temperature profile through 10 cm ribbon growth system (refer to Fig. 11).

Fig. 11. Scale of distance along growth system centerline for Fig. 10.

Table VII. Cold Shoe Temperature Measurements.

Run No.	Location (Refer to Fig. 3)	Conditions	Temperature (Degrees C)
16-217	D1	Die filling	750
	"	Growing conditions	730
	"	After 2.2 hours stable growth	723
17-080	D1	Die filling	700
	"	Seeding conditions	665
	"	Growing conditions	630
16-218	D1	Seeding conditions	692
	"	Growing conditions	675
	"	Growing with melt feeder off	665
16-218	D3	Seeding conditions	1000
	"	Growing conditions	980
16-222	D1 } D2 }	Typical control settings for growth, with afterheater setpoint at 1060°	756 261
	D1 } D2 }	As above, but afterheater setpoint at 990°	752 250
	D1 } D2 }	As above, but afterheater setpoint at 940°	730 244
	D1 } D2 }	As above, afterheater off; TC reading 720°	667 212

Table VIII. Heater Feed Bar Temperature Measurements.

Run No.	Location (Refer to Fig. 3)	Conditions	Temperature (Degrees C)
16-219 " "	E1 } E2 } E3 }	System overheated for die filling	1330 1415 1150
16-220 " "	E1 } E2 } E3 }	Furnace at operating temperature; heaters in cartridge turned off	890 900 610
16-220 " "	E1 } E2 } E3 }	Growing condition	1245 1230 1165
16-220 " " "	E1 " " "	Typ. settings for growth, but left end htr @ 500 " " " " " " " " " 600 " " " " " " " " " 700 " " " " " " " " " 900	1230 1244 1265 1290
16-221 " "	E1 } E2 } E3 }	Seeding condition	1280 1278 1163
16-221 " "	E1 } E2 } E3 }	Growing condition	1282 1279 1165

IV. CELL AND MATERIALS CHARACTERIZATION

A. Cell Characterization by C.T. Ho

1. Overview

Routine solar cell evaluation for ribbon materials grown from all three RH furnaces continues. In the multiple System 3A, a simultaneous three-cartridge growth run, 16-216, has produced 10 cm wide ribbon solar cells with conversion efficiencies of $\approx 8\%$. In the high-speed, single cartridge System 17, the baseline cell efficiency for material grown from an all-graphite system without intentional gas addition has been established around 9 to 10% at a growth speed of ~ 4 cm/min. In the experimental System 1, which at present grows 5 cm wide ribbon, the effect of turning CO_2 gas on and off during the ribbon growth has been further investigated. We noticed the equivalence to "quartz-like" behavior (i.e., similarities to material grown from quartz crucibles) in the CO_2 gas "on" condition, and "graphite-like" behavior in the gas "off" case. The possible correlation between the observed photovoltaic behavior and oxygen contained in the ribbon is supported by the detection of interstitial oxygen.

a. Multiple Growth System 3A

Run 16-216 was a multiple growth run which produced ribbon simultaneously from three 10 cm cartridges in the furnace system. The ribbons grown from each cartridge were separated and fabricated into 10 cm x 5 cm solar cells by the standard CVD diffusion process. Cell performance results under AM1 simulation measurement are summarized in Table IX.

Ribbons grown from cartridges 1 and 2 produced nearly the same averaged conversion efficiency, $\approx 8\%$, with the highest efficiency being 8.7%. Ribbons grown from cartridge 3 showed slight reductions in the output.

Table IX

Summary of Solar Cell Data for the Multiple
Growth Run 16-216. The Cells were All CVD Processed with
Area 50 to 56 cm².

100 mW/cm²; ELH Light, 28°C; AR Coated

Growth Cartridge	J _{sc} (mA/cm ²)	V _{oc} (Volt)	FF	η (%)
No. 1	21.8	.529	.661	7.6
	21.3	.525	.683	7.6
	22.4	.540	.721	8.7
	22.0	.531	.688	8.0
	24.4	.537	.609	8.0
	(22.4)	(.532)	(.672)	(7.98)
No. 2	24.1	.533	.669	8.6
	24.4	.528	.666	8.6
	22.5	.522	.637	7.5
	22.4	.524	.619	7.3
	23.9	.531	.666	8.5
	23.3	.529	.671	8.3
	(23.4)	(.528)	(.655)	(8.13)
No. 3	21.0	.515	.707	7.7
	21.0	.515	.629	6.8
	20.9	.515	.660	7.1
	21.6	.517	.684	7.6
	22.2	.522	.678	7.9
	(21.3)	(.517)	(.672)	(7.42)

The photovoltaic parameters for all the cells in this run appear to be limited by the bulk diffusion lengths, which were found to be 12 μm in typical samples.

b. High Speed Ribbon Growth System 17

Several standard growth runs using Ar as the inert gas in the main zone have been made in order to test ribbon quality in growth at high speeds (> 3.8 cm/min). Solar cells were made by standard CVD diffusion for all runs except run 17-064. Here, a split-batch fabrication run was made to delineate the cell photovoltaic behavior. Cell output data are summarized in Table X.

From the results shown in the table, we observe that (i) a baseline cell efficiency of 9 to 10% is established in the high-speed System 17 (runs 17-078, -079, and -081); and (ii) the ribbon grown with the standard Ar ambient condition shows "graphite-like" behavior in this growth system (run 17-064). These definitions, i.e., "graphite-like" and "quartz-like," will be discussed further in the following section.

c. Material from JPL No. 1

Growth run 18-191 has been made with the CO_2 ambient gas being turned "on" and "off" repeatedly during the growth process. The portions of the ribbon grown with CO_2 turned "on" have been found to contain a concentration of 4 to $6 \times 10^{17} \text{ cm}^{-3}$ of interstitial oxygen in the material, while less than $5 \times 10^{16} \text{ cm}^{-3}$ are found (detection limit of the IR spectrophotometer) in the portions with CO_2 turned "off." The ribbon was separated according to these criteria and we proceeded to examine the photovoltaic characteristics of solar cells, fabricated by using the two standard junction formation processes (PH_3 and CVD diffusions) described previously.

Table XI summarizes the output data for the cells made from the two groups of ribbon samples. It is interesting to note that solar cells prepared from the CO_2 "off"-grown ribbons have lower output than those made from the CO_2 "on"-grown ribbons which using the PH_3 process. However, they both yield similar results with the CVD process. When we examine the bulk diffusion length and the light enhancement characteristics by the IRPV technique (Fig. 12), we notice a distinctive difference between these two groups of cells. In the group of cells which was PH_3 processed, both ribbon materials show enhancements of L_n as the illumination level increases. But the lower output CO_2 "off" ribbon shows, in

Table X. Summary of Solar Cell Data for Ribbons Grown from Furnace 17. The 10 cm Dimension of the Cell Spans the Full Ribbon Width.

100 mW/cm²; ELH Light, 28°C; AR Coated

Ribbon Growth No.	Diffusion Process	J _{sc} (mA/cm ²)	V _{oc} (Volt)	FF	η (%)	Notes
17-062	CVD	24.3 24.6 24.5 (24.47)	.549 .545 .546 (.547)	.673 .640 .681 (.665)	9.0 8.6 9.1 (8.9)	Cell size 2.5 x 10 cm ²
17-065	CVD	22.0	.528	.747	8.7	5.5 x 10 cm ²
17-064	CVD PH ₃	23.0 23.7 23.8 24.3 24.2 24.2 (23.87) 20.0 20.7 20.7 19.9 20.9 21.1 20.5 (20.64)	.541 .553 .551 .542 .545 .547 (.547) .499 .509 .502 .496 .499 .503 .503 (.502)	.730 .734 .744 .664 .768 .737 (.730) .678 .728 .690 .661 .702 .660 .697 (.688)	9.1 9.6 9.8 8.7 10.1 9.8 (9.52) 6.8 7.7 7.2 6.5 7.3 7.0 7.2 (7.1)	2.5 x 10 cm ²
17-072	CVD	22.1 23.5 24.0 (23.2)	.539 .535 .544 (.539)	.753 .728 .706 (.729)	9.0 9.2 9.2 (9.13)	5.5 x 10 cm ²
17-074	CVD	23.2 23.7 23.2 23.0 (23.28)	.540 .543 .542 .541 (.543)	.739 .738 .708 .720 (.726)	9.3 9.5 8.9 9.0 (9.0)	
17-075	CVD	22.5 22.1 22.1 21.8 21.9 21.4 (22.0)	.527 .515 .529 .528 .528 .523 (.525)	.661 .612 .740 .683 .658 .718 (.679)	7.8 7.0 8.6 7.8 7.6 8.0 (7.8)	

Table X continued.

Ribbon Growth No.	Diffusion Process	J_{sc} (mA/cm ²)	V_{oc} (Volt)	FF	η (%)	Notes
17-076	CVD	22.6 22.9 22.8 23.1 22.3 23.2 22.6 (22.8)	.533 .544 .541 .537 .547 .544 .541 (.541)	.545 .657 .613 .624 .698 .635 .635 (.630)	6.6 8.2 7.6 7.8 8.5 8.0 7.8 (7.79)	5.5 x 10 cm ²
17-078	CVD	24.5 23.9 24.9 24.6 25.3 23.5 24.6 (24.5)	.548 .545 .546 .549 .551 .545 .543 (.547)	.737 .736 .695 .722 .710 .679 .677 (.708)	9.9 9.6 9.4 9.7 9.9 8.7 9.0 (9.46)	
17-079	CVD	24.5 24.7 24.4 25.0 (24.6)	.543 .541 .546 .542 .550 (.544)	.637 .671 .671 .709 .696 (.677)	8.5 8.9 9.0 9.4 9.6 (9.08)	
17-080	CVD	24.4 24.5 24.9 (24.6)	.545 .545 .535 (.542)	.591 .680 .610 (.627)	7.8 9.1 8.1 (8.33)	
17-081	CVD	25.3 24.5 24.8 25.9 (25.1)	.545 .545 .556 .550 (.549)	.729 .737 .717 .660 (.711)	10.1 9.8 9.9 9.4 (9.8)	
17-082	CVD	23.5 23.3 23.6 22.8 23.8 23.1 23.5 23.1 23.8 23.0 23.7 23.8 (23.4)	.533 .542 .544 .535 .536 .532 .534 .535 .535 .535 .543 .542 (.532)	.569 .736 .622 .722 .694 .609 .675 .687 .644 .612 .696 .614 (.657)	7.1 9.3 8.0 8.8 8.9 7.5 8.5 8.5 8.2 7.5 9.0 7.9 (8.27)	

Table XI

Summary of Solar Cell Data for Ribbons Grown from
Run 18-191 Using PH_3 and CVD Diffusion Processes.

100 mW/cm^2 ; ELH Light, 28°C ; Cell Area $\approx 14 \text{ cm}^2$; AR Coated

Ambient Condition	Diffusion Process	J_{sc} (mA/cm ²)	V_{oc} (Volt)	FF	η (%)	
CO ₂ "on"	PH ₃	27.2	.557	.753	11.4	
		27.0	.553	.750	11.2	
		28.0	.544	.752	10.6	
		26.6	.550	.744	10.9	
		24.5	.536	.734	9.7	
		26.7	.551	.769	11.3	
		26.8	.549	.701	10.3	
		27.0	.554	.742	11.0	
		(26.48)	(.549)	(.743)	(10.8)	
CO ₂ "off"		24.2	.520	.746	9.4	
		21.0	.505	.739	8.0	
		22.0	.505	.741	8.2	
		21.6	.501	.701	7.6	
		21.7	.507	.726	8.0	
		23.2	.517	.725	8.7	
		(22.28)	(.509)	(.730)	(8.32)	
CO ₂ "on"		CVD	24.5	.557	.767	10.5
			25.2	.552	.743	10.4
	26.7		.553	.768	11.3	
	(25.47)		(.554)	(.759)	(10.73)	
CO ₂ "off"	24.7		.550	.767	10.4	
	25.2		.553	.739	10.3	
	25.2		.549	.731	10.1	
	24.8		.543	.762	10.3	
	24.1		.547	.713	9.4	
	25.2		.548	.682	9.4	
	25.1		.542	.777	10.6	
	(24.9)		(.547)	(.739)	(10.07)	

(A) PH_3 Process

(B) CVD Process

Fig. 12. L_n vs. flux intensity characteristics for solar cells made from CO_2 ambient growth run 18-191 after PH_3 and CVD diffusion processes.

general; more than 50% reduction in the magnitude of L_n from CO_2 "on" at all intensity levels. In the CVD diffused group, none of the ribbon material shows enhancement in L_n , but the cells from CO_2 "off" are only 20 to 30% lower than the higher output CO_2 "on" group. In addition, at the highest illumination intensity level (10 mW/cm^2 of $1 \mu\text{m}$ light), L_n values of CO_2 "on" cells from the PH_3 diffusion have the tendency to supersede the corresponding CVD diffused cell group. For the CO_2 "off" cell group, this would not happen until much higher illumination levels are reached. These experimental results via the IRPV method are in good agreement with the conventional spectral response measurement. Figures 13(a) and 13(b) show the measured spectral responses of the representative sample in each cell group under low intensity, as well as with the superposition of a 100 mW/cm^2 ELH saturation light. The consistency between these two observations is truly remarkable.

From the diffusion length enhancement characteristics, we classify the photovoltaic behavior displayed by the CO_2 "off" group as "graphite-like," and the CO_2 "on" group as "quartz-like." The connotations are derived from previous experimental observations for material grown, respectively, from graphite crucibles and quartz crucibles, and the results clearly show the consequences of introducing oxygen into the ribbon via ambient gas control, as well as its effect on the ribbon photovoltaic property. A repeat run, 18-199, is currently in the cell fabrication process. We hope to reproduce the above observations, and establish a definitive correlation between the presence of oxygen and the photovoltaic behavior in EFG ribbon silicon.

B. Materials Characterization by J.F. Long

1. Overview

In Furnace 18 (JPL No. 1), manipulations of main zone purge argon flow rate and introduction of CO_2 into the interface region continue to result in reproducible improvements in material quality. Furnace 17 has achieved moderately high growth speeds (upwards of 4.0 cm/min) without reduction of minority carrier diffusion length. Furnace 3A (16) (for which most of the runs this quarter were developmental in nature) was operated in both single and multiple 10 cm cartridge modes, and quality consistent with the best 5 cm material grown in this furnace has been achieved.

(A) PH₃ process

Fig. 13(a). Comparison of the spectral response characteristics for typical cells made from PH₃ process under dark and 1 sun conditions.

(B) CVD PROCESS

Fig. 13(b). Comparison of the spectral response characteristics for typical cells made from CVD process under dark and 1 sun conditions.

2. Furnace 18 (JPL No. 1)

The 15 runs undertaken this quarter, for which characterization data were generated, were designed primarily to investigate further the effects of introduction of CO_2 into the furnace ambient. Problems were experienced with a few of the runs which forced early run termination and/or depressed diffusion lengths. Several runs late in the quarter were operator training runs. One run each was made with a cold shoe and to test the impact of melt temperature changes on material quality.

The run conditions and diffusion lengths are given in Table XII. Several points are noteworthy. In each run involving the introduction of CO_2 into the ambient, a significant increase in minority carrier diffusion length is experienced for the CO_2 "on" condition. Best results tend to occur when CO_2 is introduced in conjunction with reduced main zone purge rates (e.g., 18-196). The attempt to introduce a cold shoe into the system for a single run resulted, as it has under similar circumstances in the past, in depressed diffusion lengths (18-198). Finally, in run 18-205, an experiment to determine the effects of melt temperature on material properties was conducted (see Section III). As can be seen in Table XII, no effect on minority carrier diffusion length was observed.

3. Furnace 16 (JPL No. 3A)

Characterization data were generated for four 10 cm wide growth runs this quarter. Two of the runs (16-215 and -216) were multiple runs; two (16-217 and -218) were single-cartridge runs, which involved initial attempts to effect material quality improvements by manipulating the furnace ambient conditions.

Runs 16-215 and -216, both multiple runs, produced material with average diffusion lengths (22.5 and 25.1 μm , respectively) which equal the best performance achieved in Furnace 3A for 5 cm wide material.

Table XIII contains the pertinent information for run 16-217, which was a single cartridge run involving manipulation of the furnace argon flow rate as well as the growth speed. Note that significant improvement in material quality occurs at the reduced main zone purge rate. This improvement appears not to be hampered by the elevated growth speed. Sample 16-217-6 achieved the highest sample average diffusion length (average of nine measurements) seen to date on material from Furnace 3A.

Run 16-218 was the first attempt to introduce CO_2 into the furnace ambient. The gas was introduced as 1% CO_2 in argon as the main furnace

Table XII. Summary of Runs for First Quarter 1980,
Furnace 18 (JPL No. 1).

Run and Sample No.	Experimental Conditions	$\bar{L}_D$ (μm)	Comments
18-191-3M	Main zone 10 ℓ/min ; no CO_2	33.2	All references to " CO_2 " are actually 1% CO_2 in argon. For 6F, CO_2 directed on melt surface rather than on interface.
-4E	Main zone 10 ℓ/min ; no CO_2	34.3	
-4I	Main zone 10 ℓ/min ; 300 cc/min CO_2	53.0	
-4M	Main zone 10 ℓ/min ; 300 cc/min CO_2	44.0	
-5M	Main zone 3 ℓ/min ; 300 cc/min CO_2	50.7	
-6F	Main zone 10 ℓ/min ; 200 cc/min CO_2	45.7	
18-192		18.0	Aborted; melt flood.
18-193		15.5	Aborted; die failure.
18-194-1F	No CO_2	31.5	Main zone purge flow 10 ℓ/min throughout.
-2D	No CO_2	27.4	
-4G	No CO_2	26.8	
-6D	200 cc/min CO_2	37.0	
-6I	100 cc/min CO_2	31.0	
18-195-1K	300 cc/min CO_2	35.7	Main zone purge flow 3 ℓ/min throughout.
-2K	200 cc/min CO_2	36.8	
-3C	No CO_2	25.3	
-3H	300 cc/min CO_2	41.9	
18-196-1E	Main zone 10 ℓ/min ; 300 cc/min CO_2	36.9	
-1M	Main zone 10 ℓ/min ; 300 cc/min CO_2	26.9	
-3F	Main zone 2.5 ℓ/min ; 300 cc/min CO_2	59.2	
-6H	Main zone 2 ℓ/min ; 300 cc/min CO_2	43.4	
18-197-2L	Main zone 10 ℓ/min ; no CO_2	37.9	
-3D	Main zone 2.5 ℓ/min ; no CO_2	33.4	
-4E	Main zone 2.5 ℓ/min ; 300 cc/min CO_2	44.9	

Table XII continued.

Run and Sample No.	Experimental Conditions	$\bar{L}_D$ (μm)	Comments
18-198	Reduced main zone 2 to 4 ℓ/min	11.9	Cold shoe run.
18-199-1L	Main zone 10 ℓ/min ; no CO_2	35.1	
-2E	Main zone 3 ℓ/min ; 300 cc/min CO_2	59.6	
-2J	Main zone 3 ℓ/min ; 300 cc/min CO_2	51.4	
-3E	Main zone 3 ℓ/min ; 400 cc/min CO_2	52.9	
18-200		41.8	Operator training.
18-201		32.6	Operator training.
18-202		22.5	Operator training.
18-203		15.1	Operator training.
18-204		9.4	Operator training.
18-205-1D	Melt temp. $\sim 1440^\circ\text{C}$; no CO_2	16.6	Main zone argon purge rate 10 ℓ/min .
-1F	Melt temp. $\sim 1440^\circ\text{C}$; 400 cc/min CO_2	44.7	
-2I	Melt temp. $\sim 1440^\circ\text{C}$; 400 cc/min CO_2	49.2	
-3J	Melt temp. $\sim 1575^\circ\text{C}$; 400 cc/min CO_2	45.4	
-4H	Melt temp. $\sim 1440^\circ\text{C}$; 400 cc/min CO_2	43.9	
-5H	Melt temp. $\sim 1575^\circ\text{C}$; 400 cc/min CO_2	51.2	

Table XIII. Summary of Run 16-217.

Sample No.	Furnace Argon Purge Rate (ℓ/min)	Growth Speed (cm/min)	$\bar{L}_D$ (μm)
16-217-1	23.6	2.8	17.1
-2	16.0	3.3	17.2
-3	12.7	3.8	26.9
-4	9.4	3.2	19.3
-5	4.7	3.6	29.7
-6	4.7	3.8	40.3

purge gas. Flow rates from 1.45 to 2.0 l/min were attempted. No significant effect of the introduction of the CO₂ was observed ($\bar{L}_D$ = 20.2 μ m, CO₂ off; $\bar{L}_D$ = 21.5 μ m, CO₂ on).

4. Furnace 17

Eighteen 10 cm wide growth runs were made this quarter for which measurements of quality were made. The first group of runs involved the introduction of displaced dies. Secondly, a series of growth speed experiments were conducted. Finally, manipulation of the furnace ambient was attempted. Results achieved this quarter represent new high levels of material quality (i.e., run average diffusion lengths) for a cold shoe system operated at moderately high growth speeds.

Table XIV summarizes the pertinent data for this series of runs. The transition from flat to displaced dies was accomplished smoothly, although no significant improvement in material quality was observed. Several runs encompassing growth speeds from 3.0 to 4.2 cm/min demonstrated no decline in average diffusion length with increased speed. In particular, run 17-088, in which speeds of 1.9 and 3.8 cm/min were used, resulted in virtually identical (and reasonably high) diffusion length averages. The two runs (17-084 and -085) which introduced CO₂ into the cartridge purge gas resulted in no substantial improvement in diffusion length. The averages for these runs (32.3 μ m and 31.8 μ m, respectively) do, however, reflect the new consistently high levels for cold shoe growth.

Table XIV. Summary of Runs for First Quarter 1980,
Furnace 17.

Run and Sample No.	Experimental Conditions	$\bar{L}_D$ (μm)	Comments
17-071	.008 cm displacement of die top	22.8	
17-072	.008 cm displacement of die top	30.1	
17-074	.008 cm displacement of die top	27.8	
17-075	.008 cm displacement of die top	19.3	
17-076	Flat die top	24.2	
17-078	Growth speed 3.0 to 3.5 cm/min	22.2	All runs from here down utilized dies with 0.012 cm displacement of die top.
17-079	Growth speed 3.4 to 3.5 cm/min	26.2	
17-080	Growth speed 3.1 to 3.5 cm/min	20.7	
17-081	Growth speed 3.7 to 4.0 cm/min	25.9	
17-082	Growth speed 3.5 to 3.8 cm/min	14.0	
17-083	Growth speed 4.0 to 4.2 cm/min	23.6	
17-084-1A	Cartridge gas - Ar only, 1 ℓ /min	32.1	All growth at 3.8 cm/min.
-1B	Cartridge gas - 1% CO_2 in Ar, 1 ℓ /min	31.7	
-1E	Cartridge gas - 1% CO_2 in Ar, .5 ℓ /min	33.2	
17-085-1A	Cartridge gas - Ar only, 1 ℓ /min	32.9	All grown at 3.8 cm/min.
-1B	Cartridge gas - 1% CO_2 in Ar, .5 ℓ /min	28.4	
-1D	Cartridge gas - 1% CO_2 in Ar, 1 ℓ /min	34.1	
17-086	No cold shoe; growth speed 1.8 cm/min	38.6	Material much thicker (.37 mm) than cold shoe runs (~.22 mm).
17-087	Growth speed 3.8 to 4.0 cm/min	32.9	
17-088-1A	Growth speed 1.9 cm/min; $\bar{t} = .35$ mm	31.9	
-2A	Growth speed 3.8 cm/min; $\bar{t} = .20$ mm	33.1	
17-089	Growth speed 3.0 cm/min	25.9	
17-090	Growth speed 3.7 cm/min	36.4	

APPENDICES

1. Updated Program Plan

The original program plan, as amended, is still in effect.

2. Man Hours and Costs

Previous cumulative man hours were 83,769 and cost plus fixed fee was \$2,976,510. Man hours for the first quarter of 1980 are 5,812 and cost plus fixed fee is \$206,634. Therefore, total cumulative man hours and cost plus fixed fee are 89,581 and \$3,183,144, respectively.

3. Engineering Drawings and Sketches Generated During the Reporting Period

None.

4. Summary of Characterization Data Generated During the Reporting Period

See Section IV. Note achievement of $\geq 10\%$ efficiency cells for $\geq 50 \text{ cm}^2$ area from ribbon grown in high speed system (Table X).

5. Action Items Required by JPL

None.

6. New Technology

Several of the efforts here have generated items of potentially "new" technology. Some have been separately reported pending possible patent action, and all are being scrutinized for the same purpose.

7. Other

As-grown material sent to JPL.

APPENDIX 7

AS-GROWN MATERIAL SENT TO JPL - LARGE GRAINS

Ribbon 18-191-3B

Grown in JPL No. 1, no cold shoes

Clean system, doped to 1Ω -cm, p-type

Graphite crucible

Growth speed: 2.1 cm/min

Displaced die, back marked with "X" in top left-hand corner

Sample size: 5.5 cm x 10 cm

Main zone gas flow: 10 ℓ /min

AS-GROWN MATERIAL SENT TO JPL - LARGE GRAINS

Ribbon 18-199-1D

Grown in JPL No. 1, no cold shoes

Clean system, doped to 1Ω -cm, p-type

Graphite crucible

Growth speed: 2.1 cm/min

Displaced die, back marked with "X" in top left-hand corner

Sample size: 5.5 cm x 10 cm

Main zone gas flow: 10 ℓ /min