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Mobil Tyco Solar Energy Corporation
16 Hickory Drive
Waltham, Massachusetts 02254

LARGE AREA SILICON SHEET BY EFG

Program Manager: Juris P. Kalejs

First Quarterly Report - Subcontract No. 954355

Covering Period: January 1, 1981 - March 31, 1981

Distribution Date: May 29, 1981

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ABSTRACT

A multiple growth run with three 10 cm cartridges was carried out this quarter in Furnace 16, with the best throughput rates and time percentage of simultaneous three-ribbon growth achieved to date in this system. Growth speeds were between 3.2 and 3.6 cm/minute on all three cartridges and simultaneous full-width growth of three ribbons was achieved 47% of the time over the eight-hour duration of the experiment. Improvements in instrumentation and in the main zone temperature uniformity have been two factors that have led to more reproducible growth conditions in the multiple ribbon furnace.

Factors influencing ribbon quality are being investigated in Furnace 17 through the study of the effect of ambient gas species and concentrations on material properties. Growth of ribbon with the cold shoes characteristic of the high-speed systems has shown that the properties of this ribbon respond to ambient changes in much the same way as when no cold shoes are present. The best cell efficiencies attained for 10 cm wide ribbon grown with cold shoes are still below those obtained without cold shoes (10-11% versus 12-13%, respectively). It has also been shown in these experiments that meniscus CO_2 and quartz introduced in the melt (contained in graphite crucibles) are equivalent in improving the electronic quality of the ribbon in these systems.

In Furnace 18, development of a system to grow 10 cm wide ribbon in the speed range from 3-4 cm/minute without the use of the conventional cold shoes is underway.

Work on building a new multiple furnace for growth of four 10 cm wide ribbons has been started. This furnace is to be built in-house at MTSEC's expense and to be introduced into the JPL program in the last quarter of 1981.

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I. INTRODUCTION

In the past year, all essential elements have been demonstrated in accordance with the 1986 LSA project goals to qualify EFG multiple ribbon technology as a candidate for production of low-cost substrates for terrestrial solar cell fabrication. Solar cells of efficiencies over 13% have been prepared from resistance furnace-grown ribbon, 10 cm wide ribbon has been grown at speeds of 4 cm/minute, and automatic controls have been developed and successfully used during growth of 10 cm wide ribbon in a multiple ribbon furnace. It remains to integrate all these demonstrated elements into a single multiple-ribbon furnace for 10 cm wide ribbon that is the prototype unit of a large-scale facility for production of EFG silicon ribbon at the low costs necessary to achieve the LSA project goals. The milestone toward completion of the integration task scheduled for 1980, referred to as the "Technical Features Demonstration," has not yet been achieved, however, and so the program is behind schedule. Nevertheless, the necessary information to accomplish this milestone has been gathered, and suggests that it can be achieved by iterations on the present equipment design; that is, there is no technical basis for believing that the obstacles are of a fundamental nature. This view is better expressed by considering in more detail the progress that has been made in the various areas of development of the EFG prototype multiple growth units and related work.

By the end of 1979, the program had made significant progress toward a technology for production of silicon ribbon by the EFG technique that is capable of being scaled to levels required for low-cost substrates for solar cells. Growth of five ribbons, each 5 cm wide, with continuous melt replenishment for 15 hours was demonstrated, with a total output of 150 m of ribbon at speeds of 3.5 cm/minute and a machine duty cycle of over 90%. Growth of 10 cm wide ribbon in an upscaled version of the basic system had been shown to be viable, and the fundamentals of an automatic control system evolved to a point of understanding sufficient to permit construction of prototype units. Cell efficiencies up to 11.5% (AM1) had been demonstrated for large areas (~50 cm^2) for ribbon grown in single-ribbon (cartridge) furnaces at speeds of the order of 2 cm/minute, and cell efficiencies for ribbon grown in the more complex multiple-ribbon furnace at speeds of up to 4 cm/minute averaged 9%.

The work in the past year accordingly focused on development of a multiple ribbon system for 10 cm wide ribbon capable of growing three ribbons with continuous melt replenishment and automatic control capabilities, and on gaining further understanding of factors that influence material quality in high-speed growth. The Technical Features Demonstration requirement for the multiple ribbon furnace for 1980 was for a run length of eight hours, a growth rate of 4.5 cm/minute, a machine duty rate of 85% or better, operational automatic controls on one ribbon, and a ribbon quality sufficient for a 10.2% cell efficiency. In addition, an efficiency-related goal of the demonstration of a 13+% cell was required. Significant developments related to the work toward these goals which occurred in this past year have been:

(i) Characterization and development of the 10 cm cartridge to gain a better understanding of the parameters that control the die top isotherms, hence growth stability and the maximum speed capability. Reproducible growth conditions and greatly increased stability and control over ribbon width have resulted, and growth at speeds of 3.5-4.0 cm/minute is routinely possible with a control level sufficient to make multiple ribbon growth feasible.

(ii) A complete automatic control system for ribbon width control has been demonstrated. It has been proven highly successful in routinely allowing growth of 10 cm wide ribbon over time spans of the order of hours with minimal operator intervention. This system has been now installed for use with all three 10 cm cartridges of the multiple-ribbon furnace.

(iii) Improvements of cell efficiencies to the range of 10-11% have been demonstrated for 10 cm wide ribbon grown at speeds of up to 4 cm/minute. All factors relevant to quality improvements at higher speeds are not yet fully understood. However, the ambient composition influence, which has now been used to achieve cell efficiencies over 13% in lower speed growth systems, has also been shown to be operative in the case of higher speed growth. Optimization of these effects and study of additional factors which may have an important influence has proceeded through the utilization of computer modeling to study interface shape effects and mass transport phenomena in the meniscus.

(iv) Important processing effects on solar cell efficiency have been demonstrated. These show the need for the presence of oxygen during the growth process in ribbon pulled from melt contained in graphite crucibles, combined with special thermal treatment sequences during the processing, in order to maximize cell efficiencies in this ribbon. With proper attention to these factors, small (~6 cm^2) cells of over 13% have been prepared from resistance-furnace cartridge-grown ribbon.

Several factors have prevented the Technical Features Demonstration, with incorporation of the above developments into multiple 10 cm wide ribbon growth, from achieving required performance levels. Simultaneous growth of three 10 cm wide ribbons for periods of several hours has been demonstrated, but at speeds and duty rates well below those desired. Currently, solar cells made from this ribbon are in the 8% range. Unexpected irregularities in the multiple furnace main zone and interaction between thermal fields in it and the cartridge, viz., die top isotherms, are the main causes for reduced growth stability that result in lower speeds and productivity. Seed ribbon breakage has been an additional contributor to lower productivity. Work is being continued on finding tractable solutions to remedy these situations, as well as characterizing cartridge configurations that have produced ribbon at the desired speeds and with the necessary growth stability. With respect to the quality, the design changes needed to achieve control over the growth ambient have not been implemented because of the continued state of development of the multiple furnace during preparation for Technical Features Demonstrations. In summary, the differences between the individually demonstrated goals in single-cartridge growth and the multiple-ribbon furnace performance have well-defined origins, which are believed to be rooted in the inadequacy of the present design of the multiple ribbon furnace main zone configuration. The confidence that this shortfall and related program tardiness can be resolved simply by design iterations is consequently very high.

II. HIGH-SPEED GROWTH AND QUALITY STUDIES (J.P. Kalejs)

A. Overview

The 1981 goals for the LSA project that relate to quality and throughput for 10 cm wide ribbon growth are being addressed in two separate tasks in the single-cartridge furnaces operating under this program. Speed and quality optimization work is proceeding in Furnace 17 using a cartridge with cold shoes having growth speed capabilities of 4 cm/minute and above. This is aimed at development of a system for growth of uniform thickness ribbon at 200 μm (8 mils) and 4 cm/minute. Improved means of controlling the growth interface ambient composition are being tested in conjunction with ribbon quality evaluation for solar cell performance. Cell efficiencies of 10-11% are now being routinely achieved, with the goal for 1981 being to attain 12% on large area (50 cm^2) cells. Aspects of cartridge design for increased growth speed, better ribbon flatness and thickness uniformity are being evaluated in this system.

Cell efficiencies for ribbon grown in the high speed (i.e., with cold shoes) systems have not yet attained the best levels demonstrated for the ribbon grown in the low speed (i.e., no cold shoes) systems. Experiments are underway in Furnace 17 to examine the extent to which this difference may be made up by further optimization of growth conditions in the high speed system. The impact on material quality produced by the cold shoe itself is being investigated in Furnace 18 (JPL No. 1) through the development of a cartridge system for 10 cm wide ribbon capable of growth at speeds between 3 and 4 cm/minute, but without the use of the conventional cold shoe design. Questions of the effect of specific thermal profiles on ribbon quality and stress, the influence of speed on quality, and the possibility of cold shoe introduced impurities are all under consideration. Comparison of the material properties in these two systems as a function of growth parameters (speed, ribbon thickness, ambient composition) is being planned to address these problem areas.

A series of experiments with different ambient gases has been completed in Furnace 17 utilizing an improved gas distribution system for control of the ambient composition in the meniscus environment. The data show that properties of ribbon grown with cold shoes respond to ambient changes in much the same way as when no cold shoes are present. When quartz is added to the melt, ribbon interstitial oxygen levels increase and cell characteristics are obtained similar to those observed with ambient CO_2 introduction but with no quartz in the melt. Thus, the equivalence of ambient CO_2 and quartz addition to the melt in affecting ribbon electronic properties is established for cold shoe systems. These experiments have been done at speeds between 2.5 and 3.5 cm/minute. No changes in ribbon properties attributed solely to the growth speed variation in this range are observed on the basis of available data.

Acceptable growth conditions for 10 cm wide ribbon in a cartridge without cold shoes have been established in work in Furnace 18. Growth speeds are in the range of 1.8-2.3 cm/minute. Development is continuing to obtain uniform thickness ribbon and improve conditions to allow growth at above 3 cm/minute.

B. Experimental

1. Furnace 17

Experiments in Furnace 17 have continued to examine the influence of the interface ambient and growth speed on ribbon properties and solar cell performance. Ribbon doping levels have also been varied. These experiments are summarized in Table I.

TABLE I
RUN AND RIBBON DATA FOR 10 cm WIDE RIBBON GROWTH

Run No.	Speed Range (cm/minute)	Ambient Conditions (ℓ/minute)		Comments
		Main Zone	Cartridge	
17-143	2.5	6, Ar	0 - 1.5, Ar + 1% CO_2	Initial growth run at low speeds with CO_2 ambient.
17-144	2.5	6, Ar	1 - 1.5, Ar + 1% CO_2	Repeat of 17-143.
17-145	2.5	6, Ar	1 - 1.5, Ar + 1% CO_2	Repeat of 17-143.
17-146	2.5	6 - 9, Ar	1 - 2, Ar + 1% CO_2	Repeat of 17-143 with increased main zone purge rate.
17-147	2.5	6 - 9, Ar	1, Ar	Quartz in melt, argon ambient only; slow-speed growth.
17-148	3.3 - 3.4	9, Ar	0	Growth with standardized cartridge. Broken seed terminated growth.
17-149	-	9, Ar	1, Ar	Test of new die shield with standard cartridge. Poor growth conditions due to die top temperature imbalances and hot die center.
17-150	-	6 - 9, Ar	1 - 2, Ar + 1% CO_2	Repeat of 17-149 with profiled face heater (continued thermal problems with poor growth conditions).
17-151	3.7 - 3.8	9, Ar	0	Growth with standardized cartridge to establish performance baseline for new die shield trials.
17-152	3.8 - 3.9	9, Ar	0	Repeat of 17-151, study of alignment problems between cartridge and puller.
17-153	2.5	9, Ar	1, Ar	Initial use of new die shield with profiled cold shoes. Poor growth conditions due to die shield introduction.
17-154	2.5 - 2.8	9, Ar	1, Ar	Repeat of 17-153 with improved fit of die shield. Poor growth conditions due to temperature imbalances.

TABLE I CONTINUED.

Run No.	Speed Range (cm/minute)	Ambient Conditions (ℓ/minute)		Comments
		Main Zone	Cartridge	
17-155	3.0 - 3.4	9, Ar	1, Ar	Repeat of 17-153 with non-profiled face heater. Temperature imbalances with hot die center.
17-156	2.8 - 3.2	9, Ar	1, Ar	Test of new design of profiled face heater. Growth conditions still poor with hot die center.
17-157	3.2 - 3.5	9, Ar	1 - 2, Ar + 1% CO_2	Additional modifications to face heater profile. Very good growth conditions, entire growth to empty crucible without freezes.
17-158	3.1 - 3.2	9, Ar	1, Ar	Growth poor due to face heater and main zone power fluctuations.
17-159	3	9, Ar	1, Ar	Poor growth conditions due to broken seed. Continued problems with power supplies. New main zone power supply installed after run.

Ribbon was grown with essentially identical gas flow conditions in runs 17-143 to -145, with a main zone flow rate of 6 ℓ/minute of argon, and die shield inlet CO_2 concentrations in the range from 1000 to 3000 ppm. In run 17-146, the initial standard argon gas flow conditions were changed in going to a main zone purge rate of 9 ℓ/minute. In run 17-147, quartz was introduced into the bulk melt, while the combined main zone and cartridge gas purge rates were maintained in a range from 7-10 ℓ/minute with argon only. The melt was doped to 1 Ω-cm in all these runs, and the growth speed was deliberately maintained at 2.5 cm/minute throughout.

A standardized cartridge was reintroduced in runs 17-148 to -150 to compare growth with a new die shield configuration to that with the standard shield in use in Furnace 16. Growth conditions with the new shield were poor initially because of die top temperature imbalances. Further experimentation showed that changes to the face heater cross section were needed to compensate for a different temperature distribution at the die top arising from the new shield. Good growth conditions were reestablished in the standard cartridge in run 17-157 after several iterations on the face heater profile.

After run 17-159, complete rework of the main zone power leads of Furnace 17 was carried out in conjunction with the installation of a new power supply. This increased by about 30% the maximum power capability, which had been marginal in supplying enough power for 10 cm cartridge operation.

2. Furnace 18

A new main zone power supply was also installed in Furnace 18 in this quarter. In addition to providing an increased capacity, it was designed to be more tolerant of load imbalances on the three-phase power supply. These had increased in severity and had been disrupting experiments because of the high operating power levels used in the 10 cm cartridge system.

Experimental work in Furnace 18 focused on the development of a growth system for 10 cm wide ribbon that will not use the conventional design of cold shoes. Initial work was carried out utilizing a standard 10 cm cartridge with the cold shoes removed and a modified linear cooling plate/afterheater combination. The latter was redesigned to reduce the heat flux onto the die top from above the growth interface. Growth of full-width ribbon was not possible until the main zone insulation was modified to increase the cooling of the cartridge walls. With this arrangement, speeds of 1.5-1.8 cm/minute were achieved.

During the development of this system, it became evident that a considerable gradient across the die top existed in Furnace 18, which did not completely prohibit growth, but produced very nonuniform thickness ribbon. The effect of this gradient had been minimal with the cold shoes in place because the resulting greater vertical temperature gradient provided more flexibility in finding a face and end heater combination that would allow growth. Growth conditions were improved markedly after rework was done on the main zone heater power leads. These corrections reduced current imbalances in the three-phase heater circuit, and consequently the temperature difference over the 25 cm span of the main zone heater from about 100°C to less than 20°C. The resulting die top temperature difference was reduced from about 10°C to only a few degrees, at which point the imbalance was within the range that could be handled by the die top heaters.

The speed capability of the system was increased with the installation of an extra shield between the die top shield and the linear cooling plate/afterheater. This acts to reduce the coupling of the afterheater and the die top temperature fields to permit operation of the afterheater over a wide range of power levels without intolerable disruptions of the die top isotherm shape. This arrangement is needed to allow study of the effect of growth speed and post-growth cooling profile variations on ribbon stress and buckle generation processes. With the extra shield, growth speeds in the range from 1.8-2.3 cm/minute have now been realized in this system.

C. Material Quality Considerations (with C.T. Ho, G.M. Freedman and J.F. Long)

In a series of experiments carried out with the high speed 10 cm cartridge in Furnace 17, sources of oxygen in ribbon and its effect on ribbon properties have been studied by using combinations of different ambient gases and by introducing quartz into the melt contained in graphite crucibles. In one group of runs, 17-134 to -139, reported in the last quarterly report,(1) growth speeds were in the range from 3-3.5 cm/minute; in a second set of runs made in this quarter, runs 17-143 to -147, the growth speed was deliberately maintained at 2.5 cm/minute throughout. A number of different gases were used: CO in 17-134, CO_2 plus O_2 in 17-136 and -137, and CO_2 in 17-138, -139, and -143 through -146. Quartz was added to the melt in runs 17-137, -138, and -147. As-grown ribbon has been characterized by IR spectrophotometry and SPV measurements; solar cell performance and light enhancement characteristics have also been examined. The data are summarized in Tables II and III.

Ambient changes were introduced using a new die shield configuration, as described earlier.(2) Good uniformity of the test gases across the full 10 cm wide ribbon was demonstrated as judged by surface film appearance. Standard or baseline ambient conditions were chosen by fixing the main zone argon purge rate at between 6 and 10 ℓ/minute. The ribbon grown at all rates exhibited a surface film, indicating the level of CO present even at the highest of these was not negligible. When a test gas was introduced, the main zone purge rate was set at 6 ℓ/minute. When quartz was added to the melt in the graphite crucible, the surface film intensity

TABLE II

IR SPECTROPHOTOMETRIC DATA FOR RIBBON GROWN UNDER DIFFERENT AMBIENT AND MELT OXYGENATION CONDITIONS.

SAMPLE	THICK. (cm)	SPECTROPHOTOMETRY (O) (atoms/cc)	SiC	(C) (atoms/cc)	(Al) (atoms/cc)	(B) (atoms/cc)	GAS FLOW CONDITIONS CARTRIDGE GAS	FLOW RATE (ℓ/minute)	QUARTZ ADDITION
17-134-1A#2	0.047	-	✓	$2.1x10^{18}$	-	$4.2x10^{15}$	Ar	0.5	no
-3A#3	0.037	-	✓	$2.5x10^{18}$	-	$2.0x10^{15}$	0.05% CO in Ar	0.5	
-3C#2	0.020	?trace	✓	$8.7x10^{17}$	-	$2.7x10^{15}$	0.07% CO in Ar	0.5	
-3C#3	0.035	?trace	✓	$3.1x10^{18}$	-	$8.1x10^{15}$	0.07% CO in Ar	0.5	
17-136-1A	0.039	-	✓	$1.7x10^{18}$	-	$4.0x10^{15}$	Ar	1.0	no
-2B	0.032	$1.6x10^{17}$	✓	$1.4x10^{18}$	-	$4.0x10^{15}$	0.14% CO_2 + 20 ppm O_2 in Ar	1.2	
-2C	0.028	$2.8x10^{17}$	✓	$1.5x10^{18}$	-	$3.6x10^{15}$	0.23% CO_2 + 25 ppm O_2 in Ar	1.3	
-2D	0.029	trace ($\sim 4x10^{16}$)	✓	$1.3x10^{18}$	-	$3.6x10^{15}$	0.07% CO_2 + 10 ppm O_2 in Ar	1.1	
17-137-1A#1	0.034	$1.0x10^{17}$	✓	$1.8x10^{18}$	-	$3.1x10^{15}$	Ar	1.0	yes
-1A#2	0.035	$8.7x10^{16}$	✓	$1.9x10^{18}$	-	$3.2x10^{15}$			
-1A#3	0.046	$1.1x10^{17}$	✓	$3.4x10^{18}$	$1.7x10^{15}$	$3.5x10^{15}$			
-2A#2	0.041	$1.6x10^{17}$	✓	$3.0x10^{18}$	$1.7x10^{15}$	$3.8x10^{15}$	0.14% CO_2 + 20 ppm O_2 in Ar	1.2	
-2B#1	0.046	$3.6x10^{17}$	✓	$3.6x10^{18}$	$3.3x10^{15}$	$3.6x10^{15}$	0.23% CO_2 + 25 ppm O_2 in Ar	1.3	
-2B#2	0.043	$2.0x10^{17}$	✓	$3.6x10^{18}$	$2.2x10^{15}$	$3.7x10^{15}$			
-2B#3	0.052	$5.6x10^{17}$	✓	$3.7x10^{18}$	$2.9x10^{15}$	$1.6x10^{15}$			
17-138-1A-2	0.029	$4.5x10^{16}$	✓	$1.8x10^{18}$	$1.4x10^{15}$	$4.0x10^{15}$	Ar	1.0	yes
-1B	0.032	$8.0x10^{16}$	✓	$1.5x10^{18}$	$4.4x10^{15}$	$3.7x10^{15}$	0.07% CO_2 in Ar	1.1	
17-139-1C	0.049	-	✓	$1.4x10^{18}$	-	$1.9x10^{15}$	Ar	1.0	no
-1C	0.041	$6.8x10^{16}$	✓	$1.0x10^{18}$	-	$4.8x10^{15}$	0.14% CO_2 in Ar	1.14	
17-143-1C	0.036	$2.1x10^{16}$	✓	$2.8x10^{18}$	-	$1.5x10^{16}$	0.14% CO_2 in Ar	1.3	no
17-146-1C	0.040	-	✓	$1.7x10^{18}$	-	$1.6x10^{16}$	0.14% CO_2 in Ar	1.3	no
17-147-1A	0.036	$1.8x10^{17}$	✓	$1.3x10^{18}$	-	$1.6x10^{16}$	Ar	1.0	yes
-1D	0.024	$1.1x10^{17}$	✓	$8.4x10^{17}$	-	$1.3x10^{16}$			

#1,3 = Edge.
#2 = Center.

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TABLE III

SPV L_D AND SOLAR CELL RESULTS FOR GAS AMBIENT EXPERIMENTS WITH 10 cm WIDE RIBBON IN FURNACE 17. SOLAR CELLS ALL MADE WITH PH_3 DIFFUSION.

Run and Sample No.	Melt Doping ρ (Ω-cm)	Measured ρ (Ω-cm)	Gas Flow Conditions: Cartridge Gas	Gas Flow Conditions: Flow Rate (ℓ/minute)	Quartz Added	$\overline{L_D}$ (μm)	[O] x 10^{-16}	η (%) No AR
17-134-1A	4	6.5	Ar	0.5	no	21.1	-	4.40
-3A		6.4	0.05% CO in Ar	0.5		44.6	-	5.21 (-3A, -3C)
-3C		5.7	0.07% CO in Ar	0.5		33.0	trace	
17-136-1A	4	6.3	Ar	1.0	no	18.9	-	5.08
-2B		6.0	0.14% CO_2 + 20 ppm O_2 in Ar	1.2		45.3	16	6.91
-2C		5.0	0.23% CO_2 + 25 ppm O_2 in Ar	1.3		34.4	28	7.51
-2D		6.2	0.07% CO_2 + 10 ppm O_2 in Ar	1.1		27.5	4	4.93
17-137-1A	4	5.6	Ar	1.0	yes	36.5	10	-
-2A		3.6	0.14% CO_2 + 20 ppm O_2 in Ar	1.2		35.3	16	6.70 (-2A, -2B)
-2B		3.2	0.23% CO_2 + 25 ppm O_2 in Ar	1.3		30.4	20-56	
17-138-1A	2	2.9	Ar	1.0	yes	24.2	4.5	6.66
-1B		2.3	0.07% CO_2 in Ar	1.1		24.5	8	6.50
17-139-1B	4	5.4	Ar	1.0	no	27.8	-	5.35
-2A		4.6	0.14% CO_2 in Ar	1.14		41.4	7	7.33
17-143-1A	1	1.7	Ar	0.5	no	24.5	-	4.20
-1C		1.3	0.14% CO_2 in Ar	1.3		31.2	2	5.35
17-146-1A	1	1.3	Ar	2	no	18.0	-	4.42
-1C		1.3	0.14% CO_2 in Ar	1.3		30.6	-	6.28
17-147-1A	1	1.5	Ar	1.0	yes	38.3	18	7.20
-1D		1.5	Ar	1.0		44.2	11	5.63

for the baseline argon purge rates increased somewhat showing that CO levels were increasing as a result of the added quartz. Presumably the SiO evaporation from the melt interacts with graphite to contribute to the CO levels, and CO is additionally evolved directly from the melt because of the higher oxygen levels there.

<u>IR-Interstitial Oxygen Concentration:</u> The variations observed are shown in Table II. Interstitial oxygen concentrations from 5 to 18 x 10^{16} atoms/cc were observed with quartz in the melt and a standard argon ambient. Aluminum up to 4 x 10^{15} atoms/cc (~4 Ω-cm) was observed in both runs 17-137 and -138, showing quartz was indeed dissolving.

Adding oxygen-bearing gases to the argon flow in the die shield in the higher speed runs, 17-134 to -139, reproducibly raised the interstitial oxygen level. This increase was proportional to the oxygen content of the gas, e.g., CO_2 plus oxygen resulting in higher levels than CO_2 alone. CO in run 17-134 produced only trace amounts even at the highest die shield concentration. At the same time, a flow of 6 ℓ/minute of argon was maintained in the main zone, so given concentrations are further diluted as the shield gas mixes with the main zone flow that predominantly escapes out the growth slot. With argon only, this level of main zone flow is estimated to maintain a CO concentration of several hundred ppm and produces a light film on the ribbon surface.

Interstitial oxygen levels in runs 17-143 and -146 were lower than in the earlier run 17-139 at equivalent CO_2 flow rates. The growth speed was the only parameter deliberately varied between these series of runs, and it was expected that the ribbon grown at the slower speed might have the higher oxygen content given a constant meniscus source. The reasons for the lower oxygen content are not known at present.

A mixture of CO_2 and O_2 produced the highest interstitial oxygen levels, with the concentration greater when quartz was also in the melt (run 17-137) than when none was present (run 17-136). The data also indicate that the effects of ambient gases and the quartz in the melt are additive in increasing ribbon interstitial oxygen levels.

<u>SPV Diffusion Lengths:</u> The variation of the diffusion length with growth conditions is summarized in Table III. Generally, there is always an increase in the SPV values when the CO or CO_2 concentrations initially increase from the baseline argon flow conditions when there is no quartz present in the bulk melt. There is also a suggestion that the diffusion length starts to decrease as the ambient concentration is increased to higher values. This trend sets in at lower imposed ambient gas concentrations and lower interstitial oxygen levels for CO than for CO_2. ~500 ppm and [O] ~10^{16} atoms/cc for CO and ~1000 ppm and above and [O] $\geq 1 \times 10^{17}$ atoms/cc for CO_2. For quartz in the bulk melt, however, a diffusion length increase with CO_2 concentration was not observed (runs 17-137 and -138); the diffusion lengths more often varied little, and decreased with CO_2 on in one case (run 17-138).

Runs 17-143 and -146 had generally lower diffusion lengths than the earlier runs made at higher speeds. In addition, as seen from the data in Section IVB, the SPV diffusion lengths for all the runs at the lower growth speed of 2.5 cm/minute are generally poorer than for the series 17-134 to -139, and do not track the ambient variations consistently.

<u>Solar Cell Performance:</u> All processing was done with PH_3. The results are tabulated in Table III. The demarcation between ribbon grown with CO_2 on and off when there is no quartz in the melt is clear, and reproduces similar trends observed already in the case of slower speed growth (2 cm/minute) in cartridge systems without cold shoes.[1] However, the best results (run 17-139 with CO_2 only and -147 with quartz) are not as good as the best results achieved without the cold shoes. When quartz is present in the melt, the difference between cell properties

with and without CO_2 disappears with the cell parameters generally maintaining values in the range expected for the CO_2-on conditions.

Light enhancement measurements have already been shown to track the cell results in that similar dark diffusion length increases are observed with increasing illumination when CO_2 is introduced as occur with the introduction of the quartz in the melt.(1) When the quartz is present, moreover, no additional identifiable changes in light enhancement characteristics are observed when CO_2 is introduced.

Growth Speed Effects: The above discussion has pointed out that the runs from 17-143 to -146, made at 2.5 cm/minute, generally did not follow the trends in oxygen content and SPV diffusion length established in the earlier series of runs, 17-134 to -139. In addition, the solar cell results for these runs are lower, a fact which correlates with the lower oxygen content. Given the results, it is clear that deliberately going to a lower growth speed has not achieved any improvement in material quality. More data will be needed to determine whether the present results have been affected by an unknown contaminant or whether they are indicative of a real effect due to an additional factor associated with the lowering of the growth speed.

In summary, the data gathered to date show that properties of ribbon grown with cold shoes respond to ambient changes in much the same way as when no cold shoes are present. The SPV diffusion length increases, interstitial oxygen levels respond, and solar cell light enhancement characteristics are also reproduced. When quartz is added to the melt, interstitial oxygen levels increase and cell characteristics become very similar to those observed with CO_2 but no quartz in the melt. Thus, the equivalence of CO_2 and quartz addition to the melt in changing ribbon electronic properties is established at least for the growth and the processing conditions associated with the cold shoe system and PH_3 cell fabrication method used here.

On the basis of the available data, it is found that material quality was not improved in ribbon grown at lower growth speeds. No identifiable influence of growth speed on material properties is in evidence at this time.

The help of J. Mathias in obtaining the light enhancement measurements, and A.A. Menna in growing the ribbon is gratefully acknowledged.

III. MULTIPLE GROWTH AND AUTOMATIC CONTROLS (B.H. Mackintosh)

A. Overview

This reporting period follows a quarter in which the multiple 10 cm ribbon furnace was run for the first time with the full complement of three cartridges under automatic (video-based feedback) control. One additional three-ribbon run was made in the current quarter. Although the outcome of the multiple run was the most successful yet, it did not meet the 1980 Technical Features Demonstration (TFD) goals for throughput. This placed in clear focus the areas requiring progress during this year as the time approaches for a new EFG experimental sheet growth unit to be built.

Several of the problems encountered in attempting to operate Furnace 16 at the level of throughput needed to satisfy the 1980 TFD goals were related to the poor reliability of this aging piece of equipment. Other shortcomings of this machine in the areas of both throughput and product quality are related to the facts that certain portions of the equipment are not yet sufficiently well developed, and that some aspects of operation of the system are not completely understood.

The program plan for 1981 calls for a new multiple 10 cm ribbon machine to be built and demonstrated as fully operational by the end of the year. Accordingly, during this reporting period, procurement work was begun on those portions of the new machine whose design is considered to be finalized. In parallel with this effort, the experiments and development activities intended to furnish information for the design of the remaining sections of the new machine were outlined for the three existing furnaces operated under this program. The specific problem areas to be investigated using Furnace 16 are those which are unique to the multi-cartridge furnace configuration, including the following:

- Further refinement of, and characterization of, the performance of the optical automatic growth control system.

- Control system layout and operator interface; expandability of the system to an eventual 12-ribbon per operator production unit.

- Thermal interactions between the main furnace zone and the growth cartridges; interactions among the cartridges.

- Means to precisely control the flow paths and composition of furnace gases.

- Continuous melt replenishment (improved throughput and reliability; use of feed material in chunk or particle form).

- Longevity of growth system components in long run periods.

The work performed during this quarter in relation to several of these areas is described in detail below.

B. Multiple Ribbon Run 16-254

The setup for the multiple ribbon run performed in February differed from that of the most successful previous multiple run, 16-250, in two important respects. Both of these changes, namely the use of one-piece internal-capillary dies, and linear cooling plates with more closely spaced guidance surfaces, had been tested in single-cartridge runs, 16-252 and -253. The throughput performance of the system in run 16-254 is shown in Table IV along with corresponding data for the multiple runs of the fourth quarter of 1980. While the throughput of the overall system was better than in previous runs, the longest period of continuous operation between freezes of any cartridge was only about 90 minutes. In other recent runs, continuous periods of between three and five

TABLE IV

Run Data for Multiple 10 cm Wide Ribbon Growth in Furnace 16 (Model 3A).

		Fourth Quarter 1980					First Quarter 1981
	Run Nos.:	244	247	248	249	250	254
Overall System:	Duration of growth period (minutes)	279	150	317	310	595	458
	Length of ribbon produced (meters)*	12.2	[illegible]	18.9	8.2	33.0	33.8
	Time percentage of simultaneous three-ribbon growth	0	15	34	0	21	47
Cartridge #1:	Length of ribbon produced (meters)	4.1	3.8	6.0	3.2	9.6	10.2
	Time percentage of run period operating	44.8	80.0	56.7	31.2	48.1	62
	Average growth rate (cm/minute)	3.25	3.17	3.30	3.27	3.36	3.59
Cartridge #2:	Length of ribbon produced (meters)	7.6	3.0	8.9	5.0	15.6	12.3
	Time percentage of run period operating	93.5	62.0	98.7	47.0	89.7	84
	Average growth rate (cm/minute)	2.92	3.22	2.81	3.40	2.92	3.20
Cartridge #3:	Length of ribbon produced (meters)	0	1.5	4.0	0	7.8	10.6
	Time percentage of run period operating		38**	47.3		47.0	72
	Average growth rate (cm/minute)		2.6**	2.63		2.78	3.21

*All listed quantities are for full-width ribbon, except cartridge #3 in run 247.

**Estimated data.

hours have been observed. Two possible explanations for the failure of the system to display better long-term stability in run 16-254 were that higher growth rates were maintained in all three cartridges than in previous runs, and that the "tighter" guidance of the ribbon, implemented to improve its flatness, was causing binding of the ribbon as it grew out.

A thorough investigation of factors which cause the cessation of growth, and further refinement of the video-based control system, are important tasks to be carried out using Furnace 16 in the early part of 1981. Work was done on parts of this task during the current reporting period, as discussed in the following sections.

C. Causes of Cessation of Growth; Control System Performance

To date, the performance of the video-based automatic growth control system of Furnace 16 has been defined only by the duration of continuous growth periods between freezes, which have typically been 1.5-3 hours. There is no known limitation in the EFG process to the duration of continuous growth except for deterioration of the die; our experience with various EFG furnaces has included many instances of dies displaying useful life exceeding several days.

We intend, during 1981, to characterize the performance of the control system in more precise terms, to study the causes of cessation of growth, and to improve the control system so that much longer periods of unattended growth are routine. Some preliminary work on this task was done during this quarter. This work consisted of an effort to "clean up" the circuitry of the overall control system, e.g., to make small circuit modifications to reduce its susceptibility to the electronic noise in the general furnace environment, and to remedy some offset and drift problems. The effects of these improvements will be tested in the next quarter.

D. <u>Main Zone/Cartridge Temperature Relationships; Cartridge Heater Power Measurements</u>

Until recently, the operating conditions of the cartridges have been defined primarily in terms of temperatures (setpoints of the temperature control instruments and experimental temperature measurements). A decision was made during the fourth quarter of 1980 to monitor the power inputs to the heating elements of the cartridges, and to consider the ways in which these measurements could be used to guide improvements in growth performance and as a process control or diagnostic tool in a production situation. Examples of specific possible uses to which power measurements could be put are as follows:

(1) The total die heater (face heater plus end heater) power required to maintain the die top at normal ribbon growth temperature is inversely related to the heat furnished to the lower end of the cartridge by the main zone. Power measurements from the cartridges of a multiple ribbon furnace thus may be expected to indicate the relative temperatures of the various positions in the hot zone. These power measurements should also serve as a means of establishing the proper setpoint for the main zone heaters that is independent of calibration differences and differences in physical placement of the control thermocouples, which must be periodically replaced.

(2) The relative power levels of the left and right die end heaters may indicate lateral gradients in the main zone temperature profile across cartridge positions; measurement of imbalanced end heater power levels may indicate the need to further refine the hot zone temperature profile.

(3) The heating power fed to the end heaters may bear a relationship to the actual vertical temperature gradient in the die top near the ends, so that the power measurements may be used as a process-control input, e.g., for controlling growth rate. "Freezes" of ribbon growth should most frequently occur when the gradient in the die tip and meniscus near the ribbon edge becomes

zero. Precise measurement and control of the actual temperature of the die tip would be ideal for process control but is considered impractical; heater power is easy to measure and may constitute a useful control input, if its relationship with growth stability can be empirically determined.

An electronic wattmeter specially designed for cartridge power measurements was built in December 1980, and these measurements have been taken in all runs from 16-250 onward. A primary purpose of three of the single-cartridge runs made during the first quarter was to determine the relationship between the main zone setpoint and the die heater power level, and between the die heater power level and the thickness uniformity of the ribbon grown. The following statements may be made about these measurements.

The cartridge heater power measurements made in multiple run 16-254 under a condition of simultaneous full-width growth of all three stations show a considerable difference among them; they averaged 1235, 1418, and 1639 watts for cartridges 1, 2, and 3, respectively. These measurements supplement the "dummy load" temperature measurements which were the principal means used in the fourth quarter to guide improvements to the temperature uniformity of the hot zone, and show a gradual temperature gradient from one side to the other in the furnace.(1)

The experiments which consisted of growing full-width ribbon (from one cartridge) at a wide range of main zone setpoints showed no clear relationship between the thickness uniformity of the ribbon and the cartridge power level. There was not a great difference in the ease with which full-width growth could be maintained as the main zone setpoint was varied in these experiments over a range of 100°C and as the face heater temperature controller varied the face heater power over the range of approximately 800 to 1600 watts to compensate. The end heater controls and face heater setpoint could be manipulated to obtain ribbon of acceptable thickness uniformity across the width at all cartridge heater power levels.

The power levels to the end heaters varied less radically, e.g., between 80 and 115 watts each, than the face heater power levels over the 100°C main zone setpoint range. At a median setpoint for the main zone, the end heater power levels required to maintain a fixed position of the ribbon edge could be made to vary over an equally wide range by altering the growth rate and the position of the ribbon edge within the outermost 0.3 cm of the die.

The relationship between the operating power levels of the cartridge heaters and long-term growth stability has not been explored. This will be done in the course of an upcoming series of runs intended to refine and to better characterize the performance of the automatic growth control system.

E. Ribbon Thickness Uniformity

As mentioned in Section IIID, the thickness uniformity of the ribbon was closely checked in the single-cartridge runs in which the cartridge heater power levels were deliberately made to vary. These measurements showed that the current die/heater/shield/cold shoe configuration used in Furnace 16 can consistently produce 10 cm ribbon at 3.6 cm/minute, having good thickness uniformity (± 0.003 cm across the central 9 cm wide span) and average thickness of 0.020 to 0.030 cm. The necessary conditions are that the die be accurately machined, be free of silicon spillage or other features which create isotherm distortions, and that the operator take thickness measurements and use them to set the growth rate and the height of the central meniscus.

F. Ambient Gas Composition Effects

One of the important experimental tasks to be performed using Furnace 16 in the first half of 1981 will be to determine the means for precisely controlling the gas flow and composition around the growth menisci in a multiple ribbon furnace. The high outflow rates of argon and the high and widely variable concentration of CO in this gas stream passing the meniscus area are considered partially responsible for the inconsistent quality of the ribbon produced by Furnace 16, which has been lower than that produced by single-ribbon Furnace 17. As a preliminary to the design and testing of a gas-control modification for the cartridges of Furnace 16, the type of die used in Furnace 17 was tested in Furnace 16 and adopted as standard. The major role of Furnace 17 in this year's experimental program is to develop means of improving the electronic quality of ribbon material. When these means are transferred to the multiple furnace for testing, the results will be more easily interpreted because identical dies are used.

G. Construction of New Multiple Ribbon Furnace, Mobil Tyco No. 21

The machine which will constitute the Experimental Sheet Growth Unit was defined during this quarter, and procurement of its parts and equipment was begun. It is to be a furnace similar in layout to Furnace 16, but having four 10 cm growth cartridges and a central melt replenishment system. It represents one-third of the 12-ribbon per operator production unit for 10 cm EFG ribbons which was defined by the most recent SAMICS study for this process. The new furnace is designated No. 21. Its construction will be entirely funded by Mobil Tyco. On November 1, 1981, the new furnace is scheduled to be incorporated into the JPL program for a final development and demonstration period.

During the first quarter, the operating experience with the existing multiple furnace was reviewed, and a number of minor design refinements were made to those subsystems which are to be essentially duplicated for Furnace 21. Procurement was then begun on the portions of Furnace 21 which are considered to be finalized, including the following:

- Furnace chamber and associated hardware,
- Hot zone hardware, excluding heating elements and insulation,
- Cartridge power supplies,
- Temperature control instruments,
- Portions of the video control systems, including cameras and lenses, and
- Main zone power supply.

The portions of Machine 21 which are not yet finalized, and for which design inputs will be accepted from the experimental work of Furnaces 16, 17, and 18 until approximately July, are the growth cartridges, the pullers, the automatic growth control systems, and the argon supply plumbing.

IV. CELL AND MATERIALS CHARACTERIZATION

A. Cell Characterization (L.A. Ladd)

1. Overview

In order to meet the 1981 high efficiency goals which have been adopted for cells made from 10 cm wide ribbon grown in high speed systems, we believe that a systematic investigation on the interrelationships between ribbon growth parameters, ribbon material properties and cell performance parameters will have to be made. In particular, it has already been established that cell performance depends on the availability of oxygen to the ribbon during growth, the doping level, the heat treatment that the ribbon undergoes (as during cell processing), the defect level and the ribbon thickness. Our objective is to study the interrelationships between these parameters in a sufficiently systematic manner so as to be able to optimize the growth parameters for ribbon from which high efficiency cells can be made which will meet the program goals. Cell performance also depends upon cell processing parameters, but an investigation of their effects is not included in the scope of this work. Cells will be processed, however, using our best processes as developed on related in-house programs.

2. Approach

In evaluating cell performance, we think it is important to look carefully at the individual parameters as well as the overall efficiency. Our approach will be to evaluate material parameters that separately affect the cell short circuit current, open circuit voltage and fill factor. For purposes of discussion, we can group the effect of material properties on cell properties into two main categories as follows: (1) The cell short circuit current depends mainly on the minority carrier diffusion length, and (2) The cell open circuit voltage and fill factor depend mainly on the carrier concentration and on the level and type of defects and impurities which affect junction quality. These two areas of investigation will be discussed separately below. In evaluating ribbon properties and cell performance, we are also interested to know whether there is any fundamental difference between low speed and high speed grown ribbon, and some experiments to examine this possibility will be done. Some high temperature annealing experiments specifically oriented towards gaining an understanding of the role of oxygen in EFG ribbon will also be performed.

Our main emphasis in cell evaluation will be to determine how to obtain cells with high short circuit currents, as this is the principal shortfall of cells grown from carbon crucibles. This will involve a study of how to optimize the minority carrier diffusion length of ribbon in the as-grown state and of how to minimize the degradation that takes place during the type of heat treatments used in cell processing. In order to do this, we think that it will be important to understand the role of oxygen which is incorporated in the ribbon during growth. It has been shown that this can enhance the diffusion length of ribbon, both before and after heat treatment. Annealing studies to determine the effect of various heat treatments on the diffusion length and on the interstitial oxygen concentration of ribbon grown under various gas-ambient conditions will be performed. The effect of the growth conditions, ribbon oxygen level and annealing on the light enhancement effect will also be determined.

The second area of emphasis in cell evaluation will be to learn how to increase the cell voltage and fill factor. This will be done by: (1) optimizing the ribbon doping level, (2) optimizing the ribbon oxygen level, (3) studying the effect of impurity and defect concentrations upon the cell parameters, and (4) looking at the effect of heat treatment on the cell parameters. All four of these factors are known to affect the voltage and fill factor of cells.

B. Materials Characterization (J.F. Long)

1. Overview

Routine characterization of 10 cm wide ribbon grown in Furnaces 16 and 17 was carried out for a number of selected runs in this quarter. The data for Furnace 16 are given in Tables V and VI, those for Furnace 17 in Tables VII and VIII.

2. Multiple Furnace 16

A one-piece die design in use in Furnace 17 was evaluated in runs 16-252 and -253. Comparison of the average L_D values in Table V shows that these were higher with the one-piece die than they had been previously with a two-piece die that was used in runs 16-248 to -250. The data for a successful three-cartridge multiple run are given in Table IV (see Section III for additional details of the run). Some differences in ribbon properties from cartridge to cartridge are evident, but more data of this type will be needed to identify trends.

3. Furnace 17

A number of runs were made in the single-cartridge Furnace 17 with a standard cartridge in use in the multiple Furnace 16. The diffusion lengths given in Table VII indicate a marked dependence on ribbon thickness, with the best values for the thinner ribbon within the range of 25-35 μm expected for baseline material with the System 17 cartridge. The cartridges in these furnaces differ in two respects: the Furnace 16 cartridge uses a profiled cold shoe as compared to a uniform thickness or non-profiled cold shoe in use in the Furnace 17 system, and it also does not have cartridge gas but utilizes the main zone purge gas to maintain die top ambient conditions.

TABLE V

SPV DATA FOR FURNACE 16 - RUNS WITH AUTOMATIC CONTROLS AND STANDARD OPERATING PROCEDURES TO EVALUATE DIE DESIGN CHANGE.

Run No.	$\overline{\rho}$ (Ω-cm)	$\overline{t}$ (mm)	$\overline{L_D}$ (μm)
16-248[1]	1.3	0.32	9.7
-249[1]	1.1	0.35	7.0
-250[1]	1.1	0.36	19.3
-252[2]	1.1	0.32	35.4
-253[2]	2.1	0.32	22.8

[1]Two-piece die, three-cartridge run.

[2]One-piece die, single-cartridge run.

TABLE VI

SUMMARY OF CHARACTERIZATION DATA FOR MULTIPLE RUN NO. 16-254.

Cartridge Number	Sample Number	Location in Run (m)	SiC σ Front (No./cm²)	SiC σ Back (No./cm²)	$\bar{t}$ (mm)	$\bar{\rho}$ (Ω-cm)	$\bar{L}_D$ (μm)
1	1B	beginning	1.6	3.9	0.34	1.0	24.0
	2C	2	0.7	>17.2	0.36	1.3	26.7
	4A	4	0.1	1.7	0.38	1.0	26.2
	8B	6	0.1	>17.2	0.32	1.6	38.3
	12B	8	0.4	~6.9	0.42	1.1	26.5
	13A	end	0.1	0.5	0.27	1.1	47.2
AVERAGE:			0.5	~8	0.35	1.2	31.5
2	1C	beginning	0.8	1.8	0.41	0.9	13.3
	1E	2	1.5	5.0	0.41	0.9	15.2
	2D	4	2.3	2.4	0.32	1.1	26.1
	6A	6	0.6	3.3	0.30	1.3	35.5
	9B	8	0.7	7.2	0.44	1.1	22.1
	11C	end	1.1	6.1	0.32	1.4	25.0
AVERAGE:			1.2	4.3	0.37	1.1	22.9
3	1B	beginning	1.9	5.2	0.42	1.2	13.5
	2B	2	0.5	1.9	0.35	1.3	13.1
	6A	4	0.1	0.7	0.27	1.3	16.2
	9A	6	0.8	1.4	0.34	1.3	28.5
	12A	8	0.2	3.7	0.44	1.7	13.5
	13A	end	2.4	8.2	0.44	1.4	8.8
AVERAGE:			1.0	3.5	0.38	1.4	15.6

TABLE VII

DATA FOR OPERATION OF STANDARD CARTRIDGE FROM FURNACE 16 IN SINGLE-CARTRIDGE FURNACE 17.

Run No.	$\overline{\rho}$ (Ω-cm)	$\overline{t}$ (mm)	V_g (cm/minute)	$\overline{L_D}$ (μm)
17-148	1.4	0.19	3.4-3.5	36.2
17-151	1.2	0.27	3.2-3.7	28.9
17-152	1.6	0.34	3.7-3.8	17.8

TABLE VIII

SPV DATA FOR SERIES OF EXPERIMENTS IN FURNACE 17 TO LOOK AT EFFECTS OF SPEED ON MATERIAL QUALITY.

Run and Sample No.	$\bar{\rho}$ (Ω-cm)	$\bar{t}$ (mm)	Gas Flow in Cartridge	$\bar{L}_D$ (μm)
17-143-1A	1.7	0.46	0.5 ℓ/minute, Ar	24.5
-1B	1.4	0.40	0.75 ℓ/minute, 0.24% CO_2/Ar	22.7
-1C	1.3	0.30	1.14 ℓ/minute, 0.14% CO_2/Ar	31.2
17-144-1A	1.2	0.31	1 ℓ/minute, Ar	28.9
-1B	1.3	0.29	1.14 ℓ/minute, 0.14% CO_2/Ar	28.5
17-145-1C	1.5	0.32	1.14 ℓ/minute, 0.14% CO_2/Ar	32.1
-3B	1.5	0.33	1.14 ℓ/minute, 0.14% CO_2/Ar	31.8
17-146-1A	1.3	0.32	2 ℓ/minute, Ar	18.0
-1C	1.3	0.40	1.2 ℓ/minute, 0.14% CO_2/Ar	30.6
17-147*-1A	1.6	0.41	2 ℓ/minute, Ar	38.3
-1D	1.4	0.29	2 ℓ/minute, Ar	44.2

*Quartz in melt.

Additional experiments with CO_2 and quartz in the melt were carried out to extend the study started in the series of runs 17-134 to -139 to lower speed growth. CO_2 was the ambient gas used in runs 17-143 to -146; run 17-147 was with quartz in the melt and an argon ambient only. SPV results are given in Table VIII, and additional discussion and comparison of run data is given in Section IIC. As seen from Table VIII, response of the SPV diffusion length to introduction of the CO_2 was not consistent for the runs 17-143 to -146 at growth speeds of 2.5 cm/second.

REFERENCES

1. F.V. Wald et al., "Large Area Silicon Sheet by EFG," Fourth Quarterly Progress Report, DOE/JPL 954355/80-16 (February 17, 1981).

2. F.V. Wald et al., "Large Area Silicon Sheet by EFG," Monthly Progress Report, DOE/JPL 954355 (November 1 - November 30, 1980), February 13, 1981.

APPENDICES

1. Updated Program Plan

An updated plan for the period from March 1, 1981, to December 31, 1981, has gone into effect.

2. Man Hours and Costs

Previous cumulative man hours were 105,885 and cost plus fixed fee was $3,862,066. Man hours for the first quarter of 1981 are 5,806 and cost plus fixed fee is $217,191. Therefore total cumulative man hours and cost plus fixed fee are 111,691 and $4,079,257, respectively.

3. Engineering Drawings and Sketches Generated During the Reporting Period

None.

4. Summary of Characterization Data Generated During the Reporting Period

See Sections II and IV.

5. Actions Items Required by JPL

None.

6. New Technology

Any new items of technology will be separately reported pending possible patent action.

APPENDIX I

WORK BREAKDOWN STRUCTURE AND PROGRAM PLAN FOR 1981

TASK	MACHINE #	SUBTASK	'81 JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	'82 JAN
1	JPL 1 (#18)	Continue gas ambient and quality studies for 10 cm wide ribbon to supply information for use in multiple ribbon growth.			├	—	—	—	—	—	—	—	—	┤	
		Develop better ribbon guidance system to improve ribbon flatness.			├	—	—	—	—	—	—	—	—	┤	
		Study seed ribbon breakage causes to aid productivity task.			├	—	—	—	—	—	—	—	—	┤	
	Machine 17	Optimize 10 cm cartridge for growth at 4 cm/minute.			├	—	—	—	—	—	—	—	—	┤	
		Develop ambient control for use in multiple ribbon growth.			├	—	—	—	—	—	—	┤			
2	JPL 3A (#16)	Development of multiple ribbon growth with transfer of design improvements from single-cartridge units.			├	—	—	—	—	—	—	┤			
		Single-cartridge 24-hour demonstration run with automatic controls.							├	—	—	┤			
		Multiple ribbon growth demonstrations (when useful).			├	—	—	—	—	—	—	┤			
3	Machine 21	Construction of new furnace (all work to be done at MTSEC and at MTSEC's expense).			├	┄	┄	┄	┄	┄	┄	┤			
		Shakedown runs with transfer of information from single-cartridge systems.											├	┤	
4	Characterization	Ongoing electrical, crystallographic and solar cell measurements.			├	—	—	—	—	—	—	—	—	┤	
		Demonstration of large area (~50 cm^2) cell with efficiency ≥ 12.0%.													

Legend: ├───┤ Start Date — Planned Completion