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ECONOMIC IMPLICATIONS OF CURRENT SYSTEMS

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Introduction

The primary goals of this study are to estimate the value of R&D to photovoltaic (PV) metallization systems cost, and to provide a method for selecting an optimal metallization method for a given PV system. The value-added cost and relative electrical performance of 25 state-of-the-art (SOA) and advanced metallization system techniques are compared.

The data for the cost estimates comes from Flat-Plate Solar Array Project (FSA) contractors and other sources. The Improved Price Estimation Guidelines methodology (IPEG2) (Reference 1) was used to make the cost estimates.

Most of the data for the cell-performance calculations comes from a report by Martin Wolf (Reference 2). These data are used in conjunction with a grid optimization model (Reference 3) developed at JPL.

This report introduces two new concepts for evaluating metallization systems: the efficient frontier and the tradeoff slope.

Some study limitations are presented in the viewgraphs. Most notably, advanced metallization costs are usually extrapolated from laboratory-scale experiments, and back-metallization cost and performance data are not included.

Costing Methodology

The front-metallization process steps, evaluated by the IPEG2 methodology, include masking, metal deposition sintering, mask removal and plate-up. The inclusion of a copper ribbon as a strap, to increase the conductivity of the cell bus bars, increases the material costs and slightly increases the operating cost of the cell-stringing process step.

The IPEG equation is shown in the viewgraphs, as are the data sources for the process costs and the final cost breakdown for both strapped and non-strapped cells. The effects of a price swing for silver from $10/oz to $50/oz and for molybdenum-tin from 4.2¢/gm to 8¢/gm are shown in the cost tables.

Electrical Performance Calculation

In this context, the electrical performance of the solar cells studied is the ratio of the expected output power to the output power of a lossless (no resistive losses or shadow losses) cell. This calculation is made using the JPL grid optimization program (Reference 3). The program takes into account the resistive losses from the photoconductor sheet, metallization material and contact of the metal with the silicon sheet as well as the loss due to the shadowing of the grid structure. The program also uses the solar-cell operating characteristics as input values. For this study, the solar cell is assumed to be a 10 x 10-cm silicon cell with a sheet resistance of $40\Omega/\square$, maximum power voltage of 0.45 V and a maximum power current density of 30 mA/cm^2 at an insolation of 100 mW/cm^2. Each cell is designed with two bus bars and the fine grid lines evenly spaced and perpendicular to them. It is assumed that the grid lines are rectangular in cross section, of uniform thickness and homogeneous in material content.

For each process studied a maximum metallization thickness and a minimum fine-grid-line width was chosen to be consistent with that process's technology. The program then calculates the optimal bus-bar width and fine-grid-line spacing that minimizes the power loss due to the grid design.

The above optimization procedure was performed twice for every process technology. The cell performance was calculated for cells with only the metallization bus bars for current collection and again for cells having a fine copper ribbon fastened over the metallized bus-bar pattern. The one exception is for state-of-the-art (SOA) screen-printed aluminum, where bonding copper to aluminum is very difficult.

Efficient Frontier

In the viewgraphs are plots, for the SOA and advanced systems, of the process cost versus the process performance ratio. (Two connected points represent the processes using silver.) A point is said to be on the efficient frontier if there is no other point that has both a higher performance ratio and a lower cost.

A plot of only the points on the efficient frontier for both SOA and advanced systems is shown for comparison in the viewgraphs.

Tradeoff Slope

The tradeoff slope developed for this study comes from the following consideration: the total area-related system cost [total system cost minus the non-area-related power conditioning system (PCS) cost] times a change in electrical performance yields an allowable change in metallization costs. The ratio of these changes yields the tradeoff slope. (See expression in the viewgraphs.) The reference cost allocations used to make the tradeoff slope calculations come from Sacramento Municipal Utility District (SMUD) data and U.S. Department of Energy (DOE) advanced-system-level cost-goal allocations (to be published).

Metallization System Optimization

Assuming that the efficient frontier curves represent the best-known systems, then the optimal system, on each curve, is the one that is first intersected by the tradeoff slope as the tradeoff slope is moved from the highest performance, lowest-cost position to the lowest-performance, highest-cost position on the graph.

Any system improvements or new system developments that fall on the tradeoff slope line (that is, intersecting the above-described optimal system point) are now equally optimal. Any system that pushes the tradeoff slope line back to the higher-performance, lower-cost corner is an improvement in terms of the total system costs.

Process Yield Impact

Present understanding of the system process yields suggest a fairly stable yield (0.98 ± 0.01) for all systems investigated.

Two notable exceptions are: SOA evaporation, so far, has a 0.89 mechanical yield because of handling, and the Midfilm process has an 0.80 electrical yield due to sheet-resistance variations.

Conclusion

The efficient frontier and the tradeoff slope can be used to identify those metallization systems that are either already optimal systems or close enough to warrant additional R&D. Likewise, those systems that are far away from the frontier or the tradeoff slope line should be given careful consideration before receiving more R&D attention.

References

1. Aster, R.W., and Chamberlain, R.G., Interim Price Estimation Guidelines, JPL Internal Document No. 5101-33, September 1977.

2. Wolf, M., and Goldman, H., Assessment of Metal Deposition Processes, Quarterly Report, July to October 1980, DOE/JPL-954996-81/12, Jet Propulsion Laboratory, Pasadena, California, January 1981.

3. Daniel, R., Burger, D., and Stone, H., "Optimization Program/Methodology for Designing Solar Cell Grid Patterns, "Proceedings of the Electrochemical Society, May 1982.

Introduction

Purpose of this analysis:

- Compare costs and effectiveness of SOA metallization and projected metallization approaches
- Estimate the potential impact of R&D in this area

Approach:

- Use data from FSA contractors and other sources with IPEG2 to establish costs
- Use Grid Optimization Model to establish electrical performance ratios

Study Limitations

- There are many metallization processes; only 25 have been analyzed so far
- SOA metallization costs are typically based on commercial experience of industry
- Advanced metallization costs are typically based on laboratory-scale experiments and extrapolations
- There are two basic reliability issues:
  - Immediate mechanical and subsequent electrical test yields. (This has been addressed by this study)
  - Lifetime (e.g., 20-year) performance. (This has not yet been addressed)
- Compatibility with other process steps and with unusual sheet specifications will not be addressed
- Back metallization cost and performance data not included in the evaluation

Candidate Processes and Systems

PROCESS/SYSTEM	DATA SOURCE
Evaporation	
• SOA (Ti/Pd/Ag)	ASEC
• Advanced (Ti/Ni + Cu plating*)	Westinghouse
Screen print	
• SOA (Ag paste)	2.80/W, Block IV
• 1990 (Ag paste*)	JPL BPU
• SOA (Al Paste)	2.80/W. Block IV
• 1990 (Al paste*)	JPL BPU
• 1990 (Mo/Sn*)	JPL BPU, Dr. Macha
Electroless plating	
• SOA (Print resist, Ni-plate, Sinter, Wave solder)	Solarex, Motorola
• SOA (Print resist, Ni-plate, Sinter, Cu plate)	Solarex, Motorola
• Advanced (PR, Ni plate, Sinter, Cu plating*)	Motorola
Midfilm* (Ag)	Spectrolab
Midfilm* (Mo/Sn)	Spectrolab, Dr. Macha
Ion plating* (Ti/Ni/Cu)	Illinois Tool Works

*Advancement of PV SOA

Electrical Performance Methodology

- Optimum spacing and dimensions (within process constraints) are calculated using the Grid Optimization Model
- Cell efficiency is strongly influenced by sheet characteristics, junction quality, AR coating, and test conditions as well as by metallization process/system
- Therefore, *relative* electrical performance is derived in this study
- Input data that influence relative electrical performance are:
  - Metallization material resistivity, ρ_M (Ω -cm)
  - Metal-to-silicon contact resistivity, ρ_C (Ω -cm^2)
  - Metallization thickness, T (cm)
  - Fine grid line width, B (cm)
  - Resistivity of busbar strapping material, ρ_{MB} (Ω -cm)
  - Strapping material thickness, T_B (cm)
  - Sheet resistance, R_S (Ω/□)
  - Voltage at max. power, V_m (volts) and current density, at max. power, J_m(A/cm^2)

Electrical Performance Optimization Model Inputs

PROCESS/SYSTEM	ρ_M (Ω·cm)	ρ_C (Ω·cm^2)	T_1 (μm)	T_2 (μm)	B (μm)	RATIO STRAP	RATIO NO STRAP
Lossless*	0	0	–	–	0	1.000	1.000
EVAP SOA	1.6×10^{-6}	1×10^{-4}	4	8	38	0.919	0.875
EVAP Advanced	2.03×10^{-6}	1×10^{-4}	4	8	38	0.914	0.863
Print Ag SOA	4.77×10^{-6}	1×10^{-3}	8	8	127	0.892	0.790
Print Ag Advanced	4.77×10^{-6}	1×10^{-3}	12.7	12.7	127	0.898	0.820
Print Al SOA	2.00×10^{-5}	1×10^{-6}	–	8	127	–	0.652
Print Al Advanced	2.00×10^{-5}	1×10^{-6}	12.7	12.7	127	0.871	0.705
Print Mo/Sn	2.95×10^{-5}	1×10^{-3}	12.7	12.7	127	0.856	0.660
Electroless Ni/Solder SOA	2.00×10^{-5}	1×10^{-3}	50.8	50.8	457.2	0.833	0.760
Electroless Ni/Cu SOA	2.00×10^{-6}	1×10^{-3}	8	8	457.2	0.835	0.782
Electroless Ni/Cu Advanced	2.03×10^{-6}	1×10^{-4}	4	8	38	0.914	0.863
Midfilm Ag	4.77×10^{-6}	1×10^{-3}	10	10	45.7	0.913	0.821
Midfilm Mo/Sn	2.95×10^{-5}	1×10^{-3}	15	15	45.7	0.871	0.696
Ion Plating, Ti/Ni/Cu	1.76×10^{-6}	1×10^{-4}	4	8	38	0.917	0.871

*Baseline values are 40 $\Omega/\square$ sheet resistance, 0.45V max power voltage, 30 mA/cm^2 max power current density

Copper Ribbon Strap – ρ_{MB} (Ω·cm) = 1.76×10^{-6}, T_B (μm) = 63.5

T_1 = metallization thickness with strapping, T_2 = metallization thickness without strapping

Cost Methodology

This study focuses on front metallization, which can include the following process steps:

- Masking
- Metal deposition
- Sintering
- Mask removal
- Plateup

It also includes the cost of strapping with a copper ribbon in some cases; this involves an increase in material costs and a small increase in operating costs at the cell-stringing process step

COST DATA came from sources given on the next viewgraph; actual amounts of metal used came from the electrical performance model and from utilization rates reported by M. Wolf

IPEG2 processed this data to provide total costs of front metallization in terms of \$/m^2

The expression used was:

$$\frac{C(1)*EQPT + 109*SQFT + 2.1*DLAB + 1.2*(MATS + UTIL)}{QUAN}$$

where C(1) comes from the following table:

EQPT Lifetime	3	5	7	8	10	15	20
C(1)	0.83	0.65	0.57	0.55	0.52	0.48	0.46

Optimization

- The optimal metallization process/system will be on the efficient frontier

- The optimal point depends on the *total* area-related system cost. Take the total system cost and subtract FCS costs (these are not area-related). The total area-related system cost times a change in electrical performance yields an allowable change in metallization costs. The ratio of these changes yields a tradeoff slope from the expression:

1/[1,000 W/m^2 * Module Efficiency * Area-related System Costs]

- We have used SMUD data for a SOA slope and 1986 Program goals for an advanced slope in the following table

	Baseline Efficiency	Area-related System Costs	Slope
SMUD SOA	0.11	\$11/W	$8.26*10^{-4}$
Advanced	0.14	\$1.2/W	$5.95*10^{-3}$

Process Yields

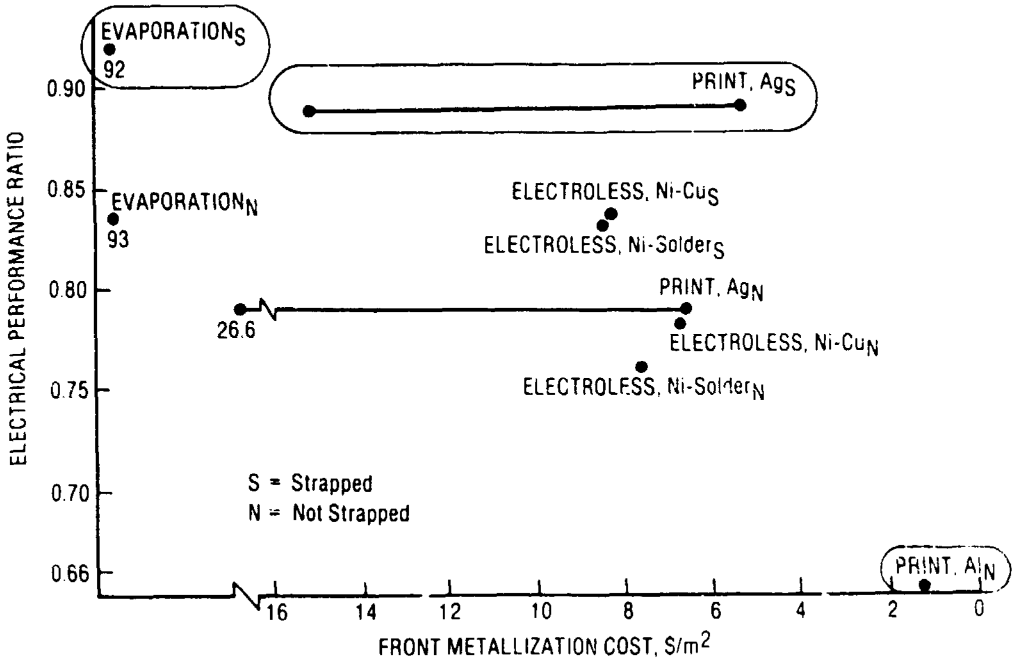
- Nearly all metallization processes appear to have essentially the same yield (0.98 ± 0.01). In these cases there is no significant relative advantage

- There are two exceptions:
    - SOA evaporation includes substantial manual handling of wafers, which results in a 0.89 mechanical yield (ASEC Block IV report)
    - Midfilm has demonstrated a 0.98 mechanical but only a 0.80 electrical yield due to sheet resistance variations. This problem may or may not be resolved through R&D

- A SOA diffused wafer will cost at least \$200/m^2 and a 10% loss adds at least \$20/m^2 to the total cost of the process

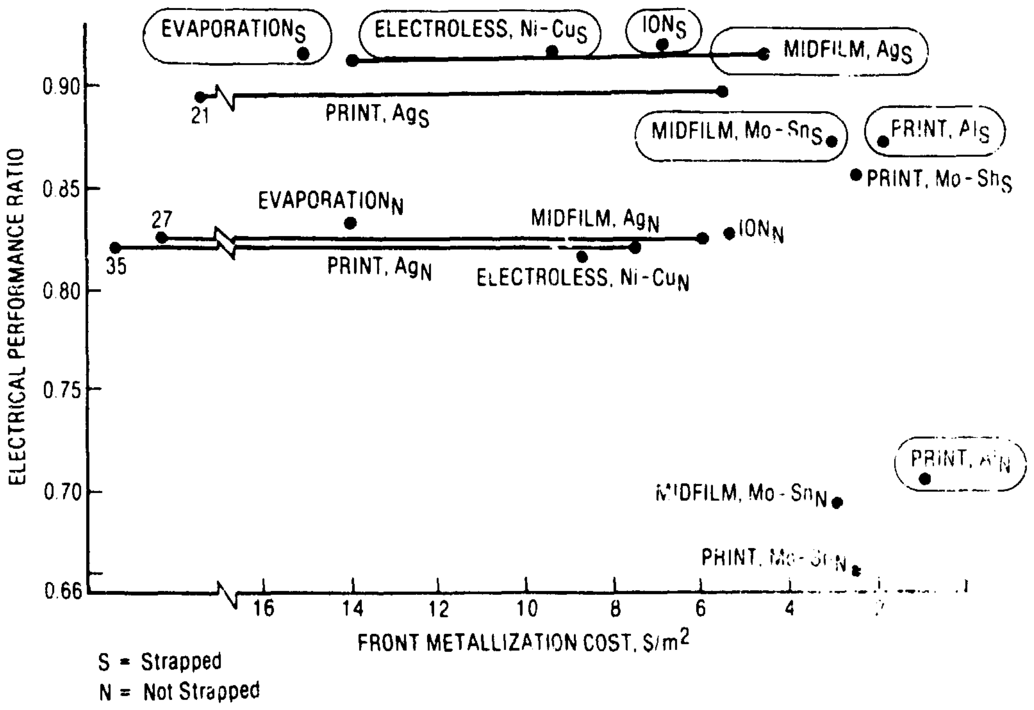
- An advanced diffused ribbon could cost from \$10/m^2 to \$40/m^2

Efficient Frontier: State of the Art

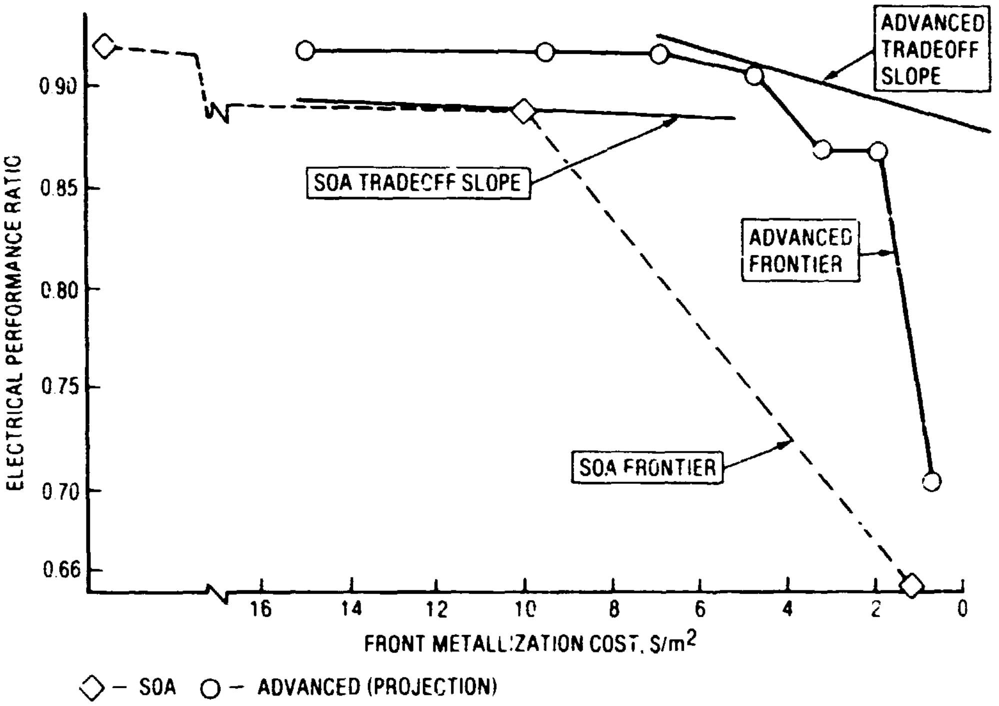


Points on the efficient frontier are as good as any other point in terms of either cost or performance; these are circled

Efficient Frontier: Advanced Systems



Combined Efficient Frontiers



Cost Breakdown, No Strapping ($/m^2)

Process/System	C(1)•EQPT	109•SQ FT	2.1•DLAB	1.2•MATS +1.2•UTIL	TOTAL
Evaporation, SOA	7.35	2.42	32.40	50.50	92.7
Evaporation, Advanced	5.26	0.98	4.25	3.61	14.1
Print, Ag, SOA*	0.71	0.30	0.52	5.09-25.07	6.6-26.6
Print, Ag, Advanced*	0.35	0.15	0.26	6.82-33.91	7.6-34.7
Print, Al, SOA	0.71	0.30	0.52	0.21	1.7
Print, Al, Advanced	0.35	0.15	0.26	0.20	1.0
Print, Mo-Sn**	0.35	0.15	0.26	1.20- 2.20	2.0- 3.0
Electroless, Ni-Solder, SOA	1.43	1.89	2.45	1.93	7.7
Electroless, Ni-Cu, SOA	1.61	1.69	2.02	1.34	6.7
Electroless, Ni-Cu, Advanced	1.35	1.75	3.35	2.15	8.6
Midfilm, Ag*	0.20	0.29	0.38	5.55-25.84	6.4-26.7
Midfilm, Mo-Sn**	0.20	0.29	0.38	1.53-2.52	2.4- 3.4
Ion Plating, Ti-Ni-Cu	NA	NA	NA	NA	6.0

*Ag price range of $10/oz to $50/oz

**Mo-Sn price range of 4.2¢/g to 8¢/g

Change in Cost Due to Strapping ($\$/m^2$)

Process/System	New 1.2•(MATS+UTIL)	Plus Strapping	New Total
Evaporation, SOA	48.68	1.0	91.8
Evaporation, Advanced	3.60	1.0	15.1
Print, Ag, SOA*	2.65-12.88	1.0	5.2-15.4
Print, Ag, Advanced*	3.94-19.52	1.0	5.7-21.3
Print, Al, SOA	0.14	1.0	2.7
Print, Al, Advanced	0.11	1.0	1.9
Print, Mo-Sn**	0.47- 0.85	1.0	2.7- 3.0
Electroless, Ni-Solder, SOA	1.63	1.0	3.4
Electroless, Ni-Cu, SOA	1.33	1.0	7.0
Electroless, Ni-Cu, Advanced	2.14	1.0	9.6
Midfilm, Ag*	2.85-12.37	1.0	4.7-14.2
Midfilm, Mo-Sn**	0.87- 1.23	1.0	2.7- 3.1
Ion Plating, Ti-Ni-Cu	NA	1.0	7.0

*Ag price range of \$10/oz to \$50/oz
**Mo-Sn price range of 4.2¢/g to 8¢/g

Summary

- **Cost and effectiveness of metallization systems have been compared**
- **Twenty-Five processes have been examined so far**
- **This study shows that metallization R&D could lead to significant advances in low-cost, high-performance processing**

DISCUSSION

HOGAN: How viable are the non-noble metal thick-film ink systems?

GALLAGHER: The data you hear will be relatively new, and I doubt that the cost information is available yet, but certainly the electrical performance and some of the physical characteristics of that structure will be.

HOGAN: What was the advanced evaporation system used?

DANIEL: That would be the nickel plus copper plating, and the information for that came from Westinghouse.

CAMPBELL: On one slide you showed the SMUD and the advanced evaporation process area-related cost. I believe SMUD was $11 and the advanced was $1.20. Can you tell me how those were derived? And specifically the $11? Does that include any module cost?

DANIEL: Yes. Those were the total cost less power-conditioning costs that are not area-related. All processing costs are in there. How the $11 came up, I'm not sure, because they came out of the details of the SMUD work.

CAMPBELL: What about the $1.20?

DANIEL: The $1.20 was one of the Project goals.

CAMPBELL: That $1.20 did not include modules, I believe. My question is: the $11 per watt you said included the price of the module, which I believe was around $4.50 or $5.00. Is that correct?

DANIEL: I don't know the individual breakdown.

CAMPBELL: OK, but it is a total cost. Is it then true that the advanced, the total cost, of getting this thing situated is $1.20?

DANIEL: Are you talking about installation in the field, or --

CAMPBELL: I am talking about something that is sitting out there, the area-related cost.

DANIEL: No. That is not true then.

WEAVER: Ron, I think he's asking are they both exactly on the same basis.

DANIEL: To my knowledge, they should be. Again, I didn't do this end of the analysis. All I was doing was giving you this information, and I would have to believe it was done on the same basis.

CAMPBELL: The only reason I am asking is, there is a tremendous difference in the area-related costs for only a 3% efficiency.

BICKLER: I think, to be on a comparable basis, the total SMUD cost was something like 15 or 16 bucks. I think it is mistaken to say that the module cost was $11. I think the $11 is simply the area-related costs.

GALLAGHER: I think so too, but can we find out before the meeting ends. We have two days and a telephone. We will get you the answer.

(EDITOR'S NOTE: The dollars quoted were for a mounted and installed facility without power-conditioning addition.)

ILES: I was a little disturbed about the yield numbers, 0.98, because for nearly all the processes it makes the Research Forum not worth doing, in many of these cases, because 98% is about as much as you would want. I suspect that because the efficiency is rattling around in there -- I think the needle just moved, and you say it is a live cell, but I think you have to look a little closer at what you mean by electrical efficiency, not in the model but in real life, because some of the newer metallization systems have a lot of problems in many respects. But the question is, whether the lifetime before it peels off is longer than the lifetime in the bulk of the silicon. I really wasn't meaning to be facetious, but I think that 98% gives everybody a very complacent feeling if you don't look at the details. I realize your problem, because not everybody will talk to you and tell you what their yields were. I am sure that most people doing screen printing have some breakage until they get completely mechanized.

DANIEL: Yes. The mechanical yields that we talked about in this discussion were from information that was provided to us through the contractors, and we are using the SAMICS-type analysis, and from what information we have this is what everybody was saying -- either the 0.97 or 0.99 mechanical yield.

WOLF: At that process step.

DANIEL: Yes. At the particular process step under discussion.

AMICK: It's a mechanical yield, not an electrical yield.

DANIEL: Yes. It is a mechanical yield, not electrical, and that of course is another entity analysis. After you have done all that, how well does the cell perform? That particular information generally is left out of the process step analysis, in terms of costing, and we try to put it back in by looking at the metallization characteristics. If we were to do the best job we could with the grid design, what kind of an electrical performance could be expected if everything was working very well? Again, there is no overlapping of the mechanical yield, and in this case, the electrical performance and the lifetime of the whole monitoring system.

RIEL: Back to the same question as Bob Campbell's. The SMUD area-related system cost of $11 -- does that include the power-conditioning cost?

DANIEL: No, in that case it does not include the power-conditioning costs.

TAYLOR: I would like to come back to Peter's (Iles) discussion of the yield question. He pointed out that there is another aspect to the yield. You have to be careful of that. And that is, yes, these processes are running along at 98% yield and then you have a yield bust. For a week or so your yield is like 40% or 50%. When you ask people what their yields are, they give you the 98% and they don't tell you about the yield bust.

WEAVER: It's the 30-year yield, that's what you really want to know.

DANIEL: Well, certainly, if the lifetime of the whole system were not all integrated into this analysis, and that point is well taken. If you are talking about an instantaneous yield, certainly, if you have this yield bust going on. Until that is solved, not only does it impact that particular cost effort, it impacts all of the upstream processes also, because you have an expected output of production and you are continuing to lose cells at that later point. You have to increase everything upstream so it increases not only the direct cost at the process step -- which, in terms of the yield, is linear if it is only a small yield (over factors of 2 it's probably not linear any more) -- but certainly the impact goes all the way up the chain, so the value-added cost incurred at the metallization process step then becomes misleading because of its impact on certain other process steps preceding it.

WOLF: This seems to exhaust the questions about this paper.