N O T I C E

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Low-Cost Solar Array Project

DOE/JPL-1012-37
Distribution Category UC-63b

Cost of Czochralski Wafers as a Function of Diameter

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Through an agreement with
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The JPL Low-Cost Solar Array Project is sponsored by the Department of Energy (DOE) and forms part of the Solar Photovoltaic Conversion Program to initiate a major effort toward the development of low-cost solar arrays.

ABSTRACT

The impact of diameter in the range of 10 to 15 cm on the cost of wafers sliced from Czochralski ingots is analyzed. Increasing silicon waste and decreasing ingot cost with increasing ingot size are estimated along with projected costs. Results indicate a small but continuous decrease in sheet cost with increasing ingot size in this size range. Sheet costs including silicon are projected to be \$50 to \$60/m^2 (1980 \$) depending upon technique used.

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INTRODUCTION

The ingot and wafering techniques being considered as part of the Low-Cost Solar Array Project (LSA) are the most mature available. Czochralski (Cz) growth and several wafering techniques have been extensively developed, and are being further fine-tuned toward cost reduction, as part of the LSA project. Recently it has been determined that the cost of Cz ingots can be reduced significantly by increasing their diameter. But wafering speed, and--more critical--silicon utilization, tend to decrease as size increase. This suggests that an optimum size for Cz ingots exists in terms of total wafer cost/m^2; the purpose of this analysis is to define that optimum.

APPROACH

The approach used to arrive at a relationship between sheet cost and wafer diameter is to select rates, times, cost, etc., based on technology projections and to make straightforward calculations from those selections. Obviously the critical elements are the selections, and the credibility of the assumptions used. It would be pointless to make calculations based on today's techniques; there is no question that such techniques fail to meet LSA Project requirements. So an effort was made to use aggressive but rational projections, and in some cases, more than one projection was used to depict sensitivity. In all cases, projections are based on discussion with contractors and qualified personnel in the technical areas concerned, and these numbers were further reviewed and consolidated by members of the Large-Area Silicon Sheet Task. In all cases, costs are expressed in 1980 dollars.

ASSUMPTIONS

In some cases the assumptions used in these calculations can be included in the form of a simple list; such a list is given in Table 1 for Cz growth, and in Table 2 for wafering. In Table 2, two internal-diameter wafer-cutting scenarios are presented as a result of significant inputs from different sources. Specific levels of performance are projected based on changes in performance with ingot diameter. Equations were then determined from these plots for use within the calculations. Equations were selected on the basis of maximum r^2 from linear, exponential, logarithmic, and power series, where r is a correlation coefficient. Such performance projections are included in Figures 1 through 4 and will be discussed individually.

Table 1. Assumptions for Cz Growth

Crystal diameter (cm)	10	12.5	15	17.8
Pulling yield (%)	83	81	82	84.3
Growth rate (cm/h)	10	10	10	10
Crucible Cost ($) (includes misc.)	242	300	300	330
Ingots per crucible	5	3	4	5
Kg per run	100	134	160	250
Equipment cost ($K)	175	175	175	180
Equipment floor space (ft^2)	100	100	100	100
Machines per operator	3	3	3	3
Labor cost ($K/shift/yr)*	12.2	12.2	12.2	12.2
Argon, power, water ($/run)	523	531	555	765
Cycles/yr	100	102	99	80

*4.7 shifts required for full-time operation

Table 2. Assumptions for Selected Wafering Technologies

	Unit	ID #1	ID #2	FAST
Area produced	m^2/yr	$5x10^6$	$5x10^6$	$5x10^6$
Yield	%	95	95	95
Manpower	Saws/operator	12	6	10
Blade life	Cuts	6,000	3,500	7,500*
Blade cost	$	35	49	73
Misc. supplies (includes elec.)	$/blade	7	7	7
Machine cost	$	49,000	56,000	56,000
Labor cost**	$/yr/oper.	14,000	14,000	14,000
Machine floor area	ft^2	30	30	80
Working year	days	365	365	365
Poly Si Cost	$/kg	14	14	14

*1,500 slices/cycle x cycles/pkg
**4.7 operators required for full three-shift operation

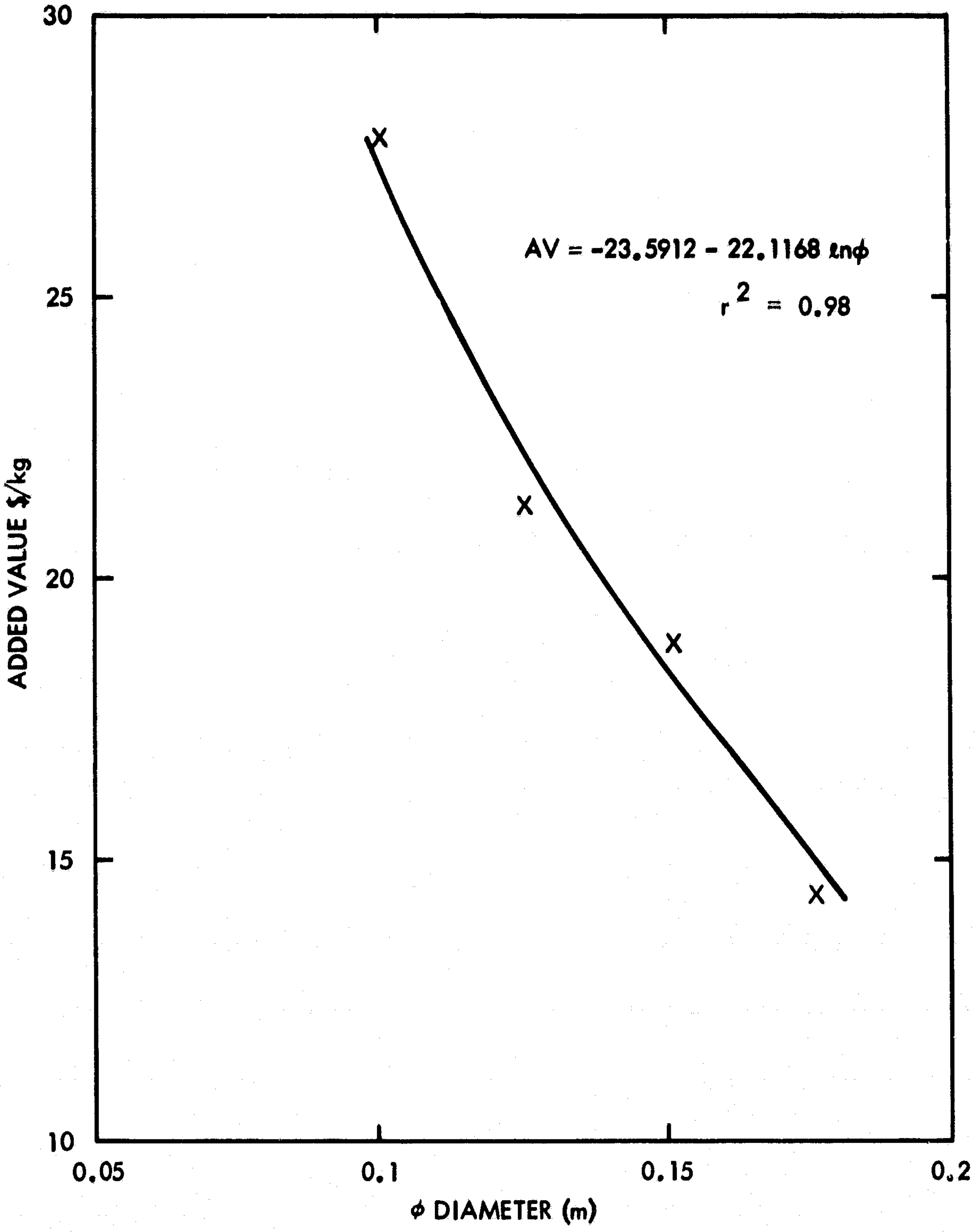

Figure 1. Added Value (AV) for Cz Ingots as a Function of Ingot Diameter

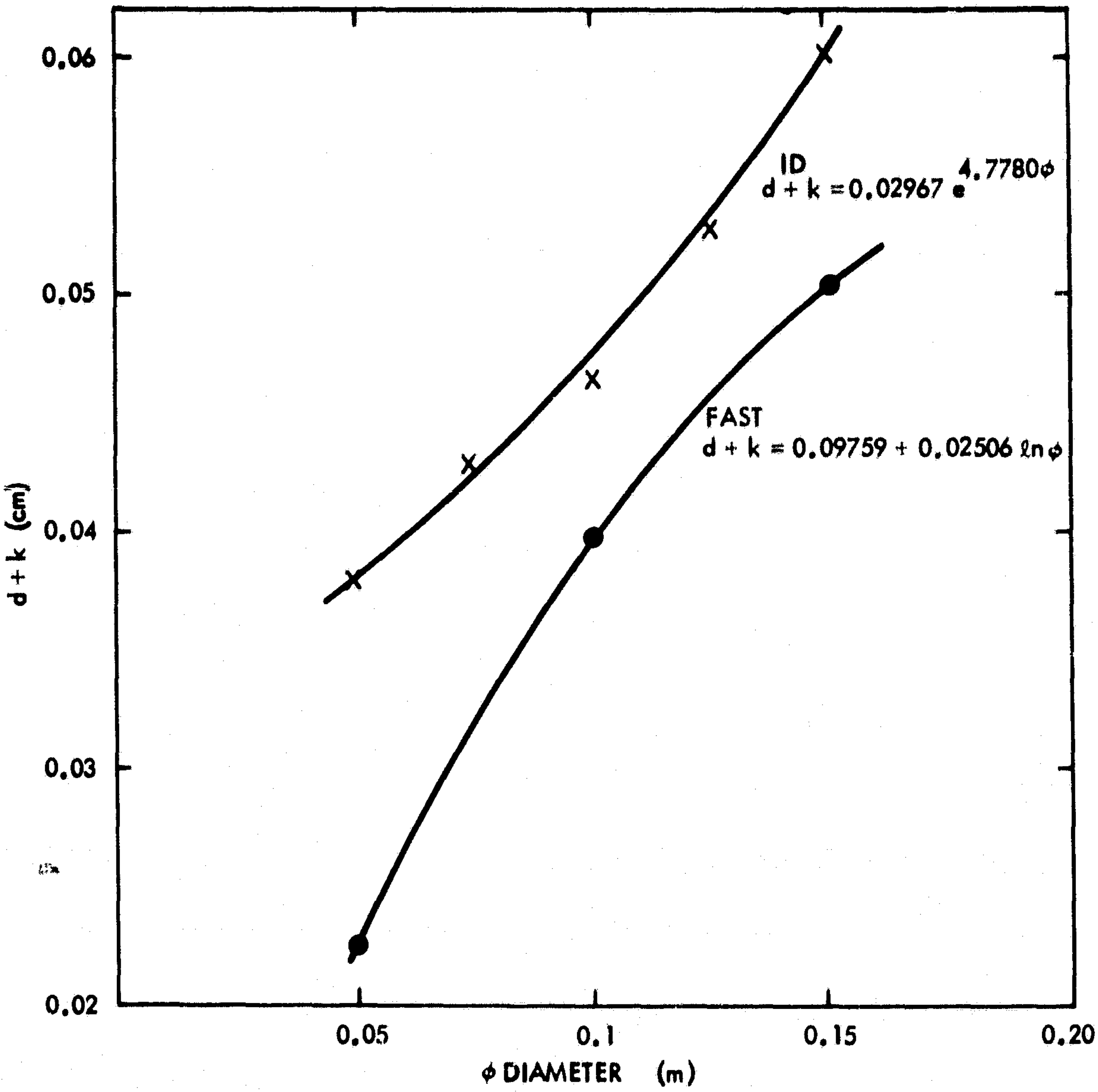

Figure 2. Projected Wafer Thickness + Kerf (d + k) as a Function of Ingot Diameter.

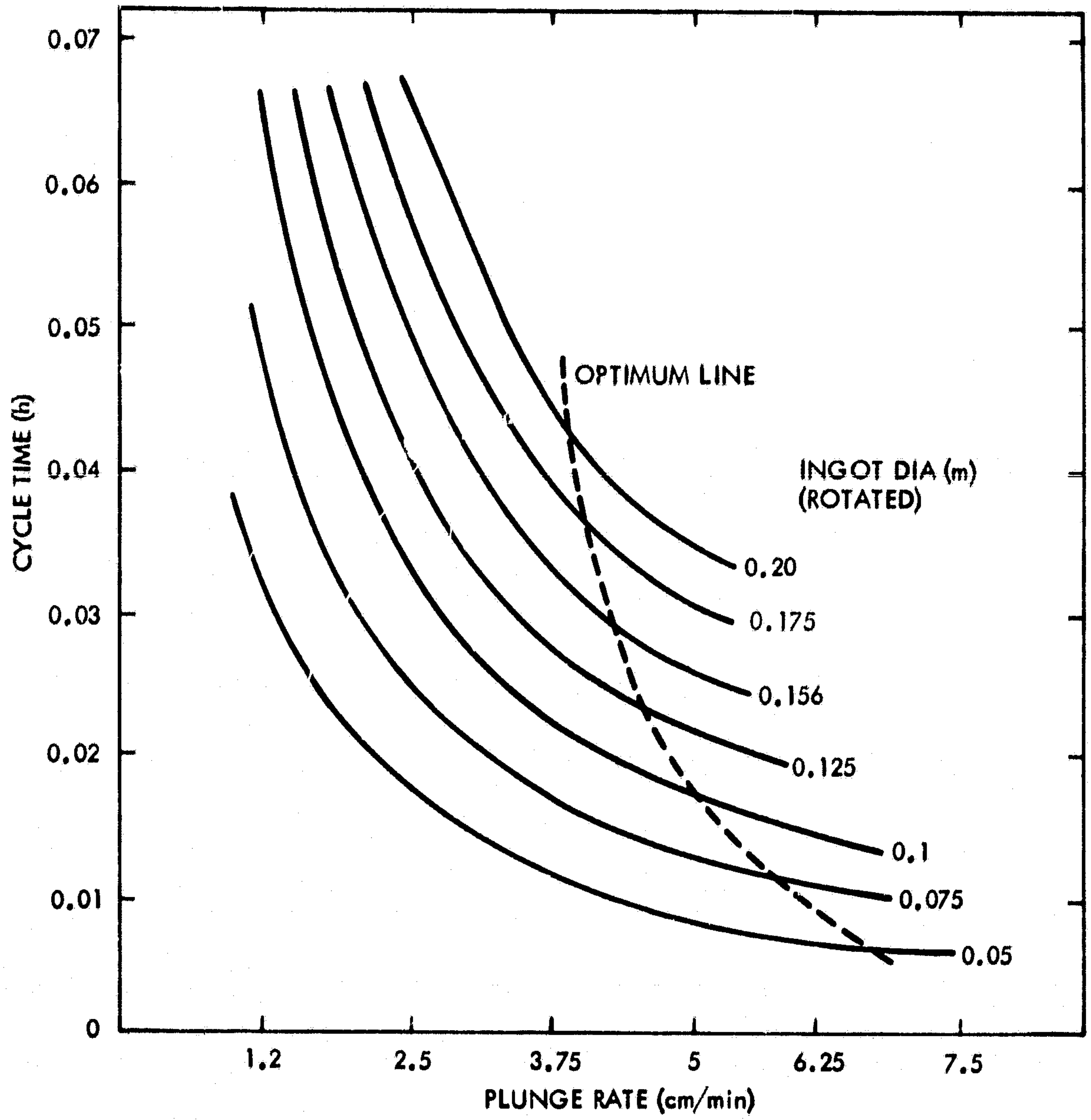

Figure 3. Cycle Time for ID Wafering for Various Plunge Rates and Ingot Diameter (with Ingot Rotation).

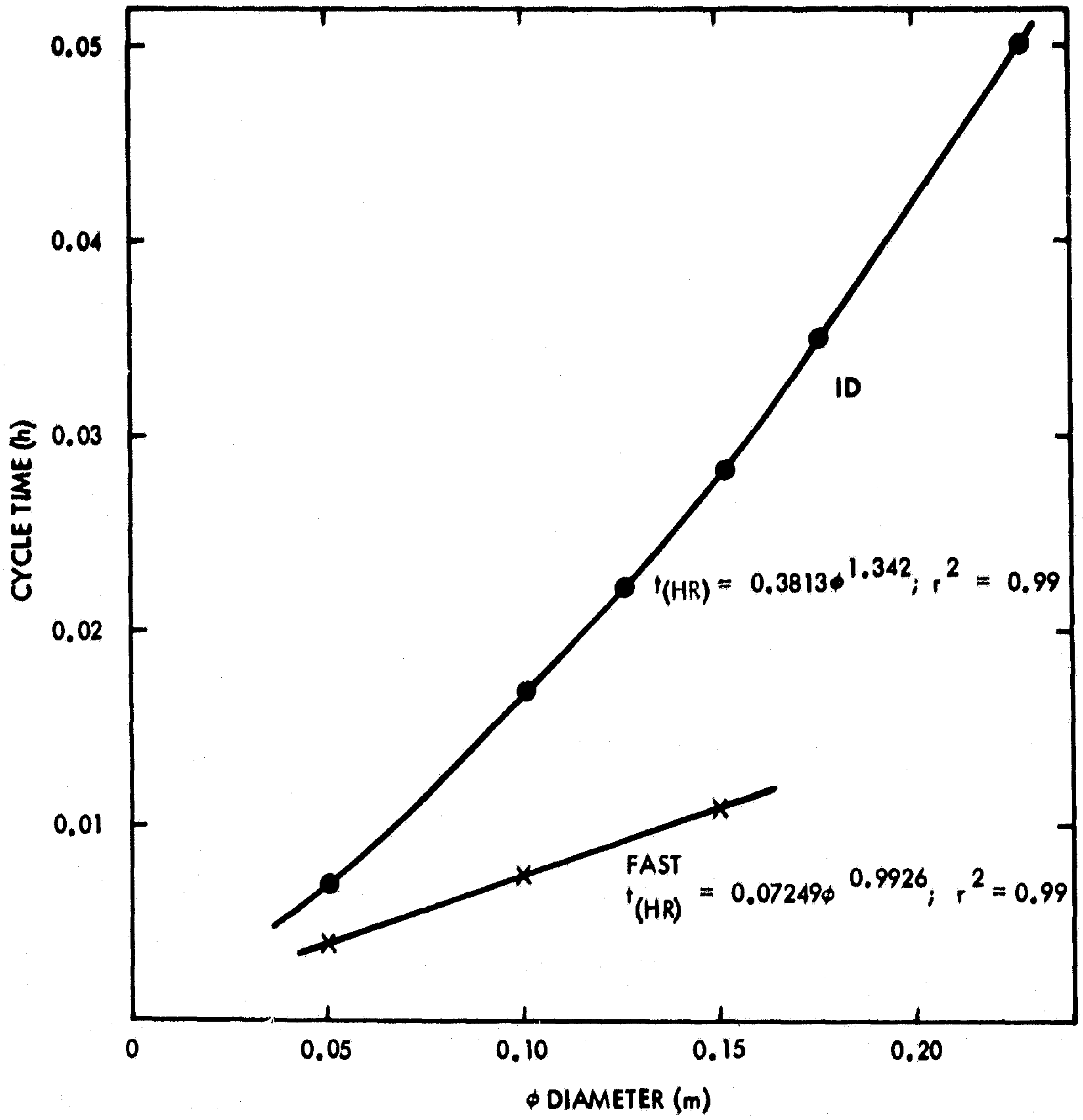

Figure 4. Cycle Time vs Diameter for Slicing. ID Data, Assuming Rotation, Taken from Optimum Line in Figure 3.

DISCUSSION

Figure 1 depicts the expected relationship between add-on cost for Cz growth and ingot diameter. The crosses shown in the figure are the data from Table 1, where a sequential melt replenishment technique is used.

The wafering analyses developed used data on internal-diameter (ID) wafering and fixed-abrasive slicing technique (FAST) wafering for reasons of availability. Other wafering analyses can be included as needed. Minimum achievable slice thickness plus kerf (d + k) and (AV) for wafering are expected to be a function of diameter. Projections of achievable values of d + k are shown in Figure 2. Initially, independent projections of ID capability were made by two of the authors (ML and CR) and the average of these is designated by x. These are based on experience, discussion with contractors and the present state of the art. A projection consistent with Task II goals of 25 wafers/cm of 10-cm dia would produce more optimistic numbers. Projections were made for FAST based on contractor estimates. It should be emphasized that production operation of FAST technology is not at hand.

It should be noted that any increase in d + k will be accompanied by increased wafer cost. Assuming that all other growth and wafering costs are constant, this cost is then solely the amount of additional silicon in the form of Cz ingot that is utilized. Thus for each 25 m (0.001 in.) of total thickness of 10-cm-dia wafers, the cost will increase by

$$(\$14/\text{kg} + \$27.5/\text{kg}) \times 2330\ \text{kg/m}^3 \times 25 \times 10^{-6}\text{m}^3/\text{m}^2 = \$2.41/\text{m}^2$$

and for 15-cm wafers, $\$1.89/m^2$. These are minimum increases as they do not include overhead charge, or burden, on the incoming silicon.

Next, a projection of the added value (AV) associated with cost of wafering was developed. These analyses consider recent technology advances and projections. For example, recent work suggested that ingot rotation is useful in reducing cycle time for ID wafering and is therefore planned here. Alternative approaches such as multiple-ingot cutting by ID also have potential. However, with ID slicing at least three ingots must be cut simultaneously or rotation becomes impractical. Unfortunately, ID saws capable of handling three or more 10-cm-dia ingots do not exist. Figure 3 was prepared to obtain a projection of cutting time for ID wafering as a function of diameter. Cycle time for various diameters are given by an optimum line. This is considered to be the maximum rate before the onset of serious yield losses. The values here are based on experience, reports and contractor discussions. From these optimum values, Figure 4 was prepared; it gives the required equation for cycle time as a function of ingot dia (with rotation). Figure 4 shows cycle time (per wafer) based on total wafer production and total cutting-cycle time for FAST wafering.

Next an Interim Price Estimation Guideline (IPEG) analysis was conducted on wafering added value based on the assumption and definitions. Scenario ID #1 is shown here and an identical procedure but different assumptions were used with the second ID scenario and with FAST.

A_s = area/slice (m^2)

t = cycle time = f (dia, plunge rate, etc.); see Figure 4

N_m = number of machines = $\frac{N_s \times t}{24 \times 3654 \times 0.95}$

N_s = number of slices = $5 \times 10^6/A_s$

N_o = number of operators = $N_m/12$

N_b = number of blades = $N_s/6000$

$$\$/m^2 = \frac{\$136(30 \times N_m) + .49(N_m \times \$49K) + 2.1(4.7 \times \$14K \times N_o) + 1.3(N_b \times \$42)}{5 \times 10^6 m^2}$$

Inserting

$$A_s = \frac{\pi}{4}\phi^2(\phi = \text{dia } \{m\}),\ N_m,\ N_o,\ N_b,$$

and

$$t = 0.3813\phi^{1.342} \text{ (Figure 4)};$$

we find

$$\$/m^2 = \frac{1}{\phi^2}(1.781\phi^{1.342} + 0.0083)$$

Thus the wafering added value can be represented by an equation of the form

$$\$/m^2 = \frac{1}{\phi^2}(a\phi^b + c)$$

The values of these parameters for each wafering technique are as follows:

	a	b	c
ID	2.31	1.342	0.0116
ID	3.182	1.342	0.02648
FAST	0.495	0.9926	0.018

An additional Cz ingot cost is for OD grinding. A present estimate would be $1/linear in. of 10-cm ingots with the cost scaled according to the circumference over this limited diameter range.

Thus, $(\$/m^2)_{grind} = \frac{(10\phi_m \times \$1)}{(m^2/in.)} = \$10\phi/(\frac{\pi\phi^2}{4} \times \frac{0.0254}{d \times k})$. This results in an additional $1 to $2/m^2.

$$(\$/m^2)_{wafer\ AV} = \frac{1}{\phi^2}(a\phi^b + c) + (\$/m^2)_{grind}.$$

The relationship between diameter and AV for all wafering techniques is shown in Figure 5 for information.

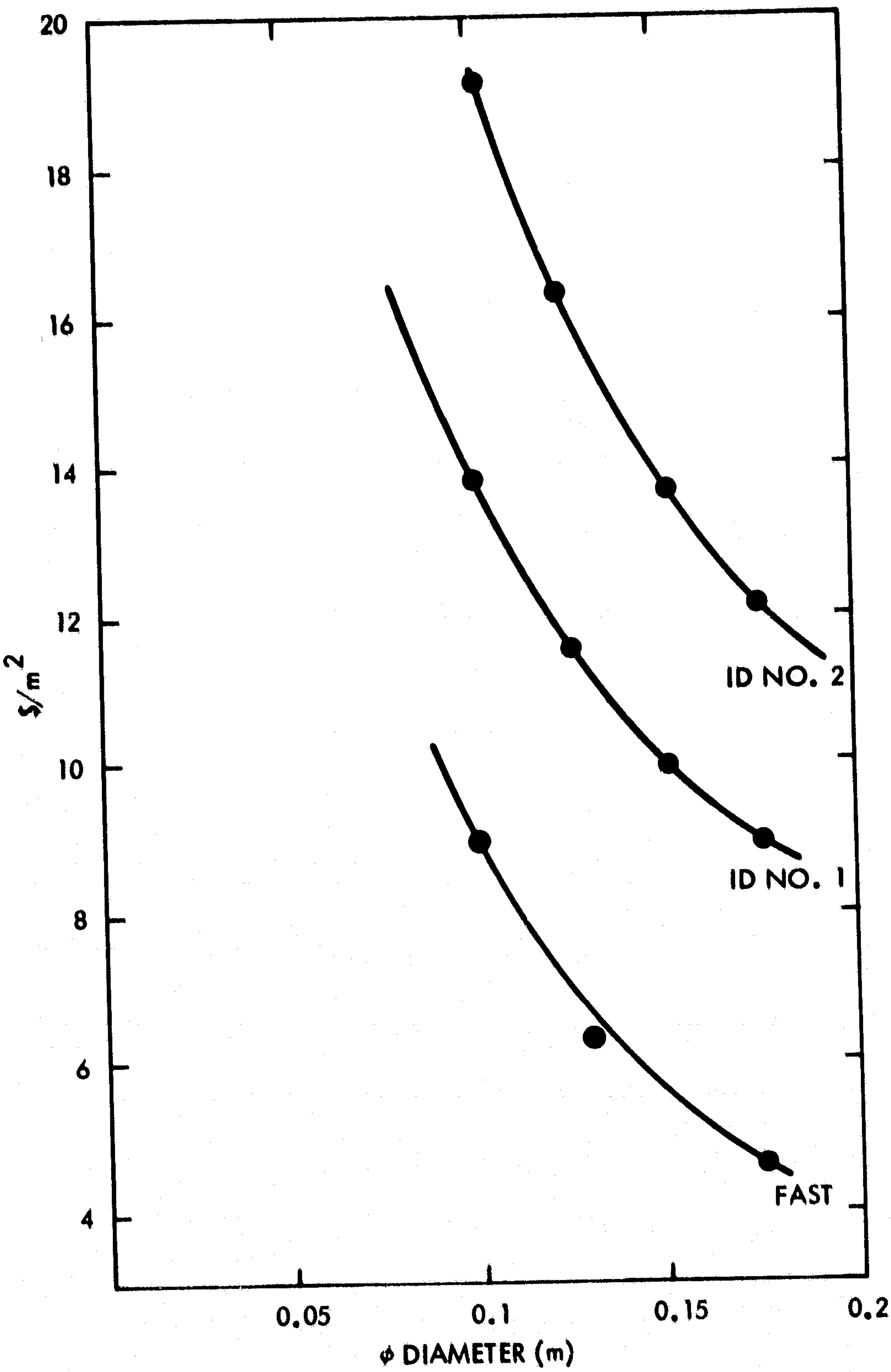

Figure 5. Wafering Added Value (Includes OD Grinding)

Finally, silicon sheet cost was calculated as follows:

$$(\$/m^2) = (\$/m^2)_{wafer\ AV} \text{ for all wafering approaches}$$
$$+ \ (\$/kg)_{Si} \times (kg/m^2)$$

$(\$/m^2)_{wafer\ AV}$ from Figure 5

$$(\$/kg)_{Si} = (\$14 + Cz\ AV) \text{ from Figure 1}$$

$$(kg/m^2) = (kg/wafer/m^2/wafer)$$

$$kg/wafer = (d + k) \ (A_s) \times \text{density Si /yield}$$

Additionally, a question exists as to the inclusion of a 30% overhead charge burden on the polysilicon used in the process. This may be accommodated by raising the price of silicon by 30% to $18.2/kg. Figure 6 shows plots of total sheet costs without burden, as well as sheet-growth added value for the various wafering techniques used. (The latter is calculated by subtracting polysilicon used at $14/kg or $18.2/kg from the total sheet cost). Note that cost continues to decrease as larger ingots are processed. It should be emphasized, however, that the data at large-ingot sizes is more speculative; hard data for these large sizes are not available. Indeed, all scenarios are based on projections, even including 10-cm technology, which is considered standard; with larger sizes the confidence level is lower. The sheet costs shown in Figure 6 thus probably represent a lower limit of achievement for this technology.

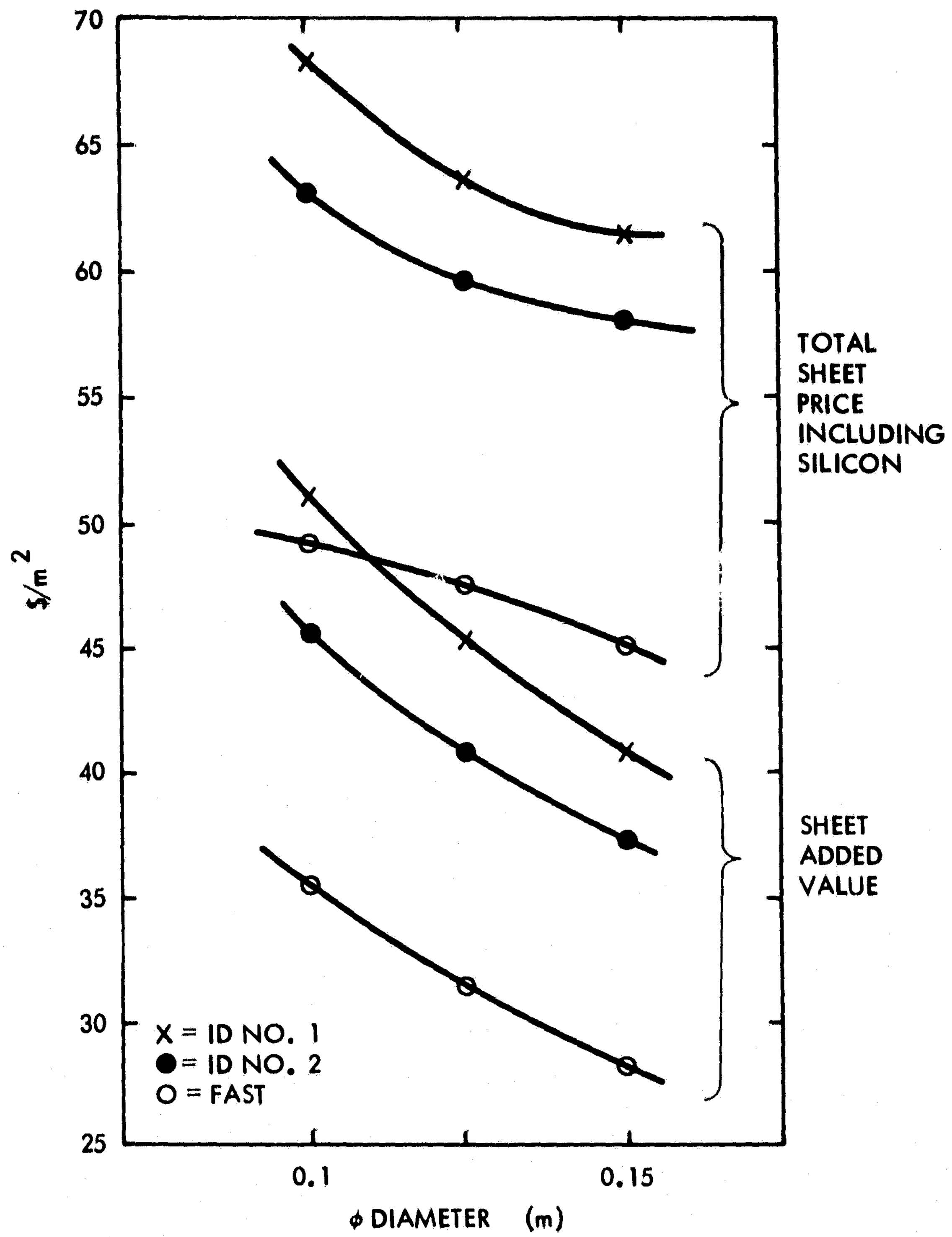

Figure 6. Total Sheet Price and Sheet Added Value as a Function of Diameter for Cz Growth and Various Wafering Scenarios (Adding Burden of 30% on Polysilicon Increases Total Sheet Price by $5/m^2$.)

CONCLUSIONS

1. Extending technology to >10-cm dia could produce a cost advantage.

2. Considering total sheet cost, the impact of diameter in the 10- to 15-cm range is 5%.

3. Technology projections to >10-cm dia are more speculative and are of lower confidence.

4. Cz growth and wafering suggests a minimum total wafer-cost projection of $\$63/m^2$ with ID wafering and $\$48/m^2$ with FAST wafering.