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White Paper: Benefit of FBR Granular Polysilicon to increase efficiency of PV ingot manufacturing by increasing crucible polysilicon charge weight

REC Silicon has commercialized Fluidized Bed Reactor (FBR) technology to produce Granular polysilicon on a wide scale basis. FBR technology offers significant benefits to the end-user that enable increased throughput, decreased cost and increased profit in the PV ingot manufacturing process. The word "Granular" is a reference to the size and geometry of the output of an FBR polysilicon reactor which is small round beads (Figure 1). This form factor offers several advantages over traditional Siemens chunk polysilicon as illustrated in Table 1.

Figure 1. *Siemens Chunk and FBR Granular Polysilicon*

Bulk Packaging	REC Silicon Granular polysilicon is packaged in 1,200 kg Flexible Intermediate Bulk Containers (FIBCs). FIBCs require less handling and are easier to unpack than traditional packages thereby reducing handling costs. FIBCs produce less waste than traditional packages.
Automation Potential	Because Granular polysilicon is composed of small round beads, it is a flowable material. This means that end-users can take advantage of process automation opportunities such as automated material transport, crucible loading, top-off and recharge.
Process Efficiency	Granular polysilicon enhances PV ingot manufacturing process efficiency by increasing the amount of yieldable ingot that can be harvested during a production cycle thereby increasing throughput, reducing production cost and increasing profit. This is accomplished by maximizing the initial polysilicon charge weight of the crucible during filling and reducing crucible loading time. Further gains can be achieved by employing top-off and recharge strategies.

Table 1. *Benefits of REC Silicon FBR Granular*

Introduction (cont'd)

A known benefit of FBR Granular polysilicon is its ability to increase the amount of yieldable ingot that can be harvested during a production cycle. This benefit is realized during the initial filling of the crucible by significantly increasing the crucible charge weight prior to melting. Greater efficiency gains can be achieved by employing techniques such as top-off, i.e. adding polysilicon to the crucible after the initial melt to raise the molten silicon level towards the top of the cruci-ble; and recharge, i.e. replenishing the melt as the ingot is pulled. The benefits of recharge for polysilicon ingot manufacturing have been documented previously in the paper *Multiple Batch Recharging for Industrial CZ Silicon Growth* published in the Journal of Crystal Growth and in a poster published by the US NREL titled *Characterization of Czochralski Solar Cells Grown with a Recharge Process*.

This paper serves to document a crucible loading test conducted by REC Silicon at our Moses Lake facility in February 2011. In addition it will extrapolate those results to create a model of benefits when FBR Granular is used on a plant scale. It will demonstrate that PV ingot manufacturers can increase initial crucible load weights by 29.3% while reducing loading time by 41.0%. Furthermore, it will demonstrate that the use of FBR Granular at the plant scale will increase total yieldable ingot produced per year by several hundred tons while reducing consumables cost by several million dollars, and providing other benefits.

Crucible Loading Test Results Summary

The crucible loading test confirmed that during the initial crucible loading stage the use of a 50% Siemens chunk/50% FBR Granular blend increased crucible charge weight by 29.3% and reduced crucible loading time by 41.0% compared to a 100% Siemens chunk blend. A summary of the test results is illustrated in Table 2. Further details regarding the crucible loading test are included in Appendix A.

> PV ingot manufacturers can increase initial crucible load weights by 29.3% while reducing loading time by 41.0%

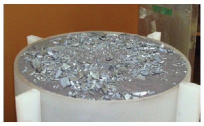
Blend	Time to fill	Improvement vs. 100% Siemens	Improvement vs. 100% Siemens	Weight	Improvement vs. 100% Siemens	Improvement vs. 100% Siemens	Filled Crucible Illustration
100% Siemens	48.4 min	NA	NA	63.8 kg	NA	NA	
100% Granular	2.3 min	46.1 min	**95.3%**	66.4 kg	2.6 kg	**4.0%**	
58% Siemens 42% Granular	37 min	11.4 min	**23.5%**	82.0 kg	18.2 kg	**28.5%**	
50% Siemens 50% Granular	28.6 min	19.9 min	**41.0%**	82.5 kg	18.7 kg	**29.3%**	

Table 2. *Summary of Crucible Loading Test Results*
Note: The results in this table are based on the crucible being filled to the top level with the crucible lip.

Benefit of Using FBR Granular at the Plant Scale

Based on the results of the crucible loading test, a hypothetical case study was created to quantify the benefits that a PV ingot manufacturer can receive by using FBR Granular on a plant scale. A set of assumptions was made to construct a model. The assumptions used for the model were confirmed based on customer feedback to represent a plausible scenario that might exist at a PV ingot manufacturing facility. The model assumes that a monocrystalline PV ingot manufacturer has a plant with 300 mono pullers using 90 kg crucibles to produce ingots intended to produce 156 x 156 mm wafers with 100% asset utilization, 90 hours per year per puller maintenance, in-situ crucible loading and $1,000 per cycle consumable costs.

The model only reflects the increased benefit of FBR Granular gained from crucible loading verified in our crucible loading test. Benefits of top-off and recharge are not included in this model. Employing these strategies will significantly increase the efficiency gains from using FBR Granular. Further investigation will be conducted to quantify the benefits of top-off and recharge.

Two blends were compared: 100% Siemens chunk and 50% Siemens chunk/50% FBR Granular.

The model assumes that for a 100% Siemens blend, the crucible load for each puller cycle is 95.7 kg with a loading time of 72.65 minutes, melting time of 6 hours, pulling time of 48 hours, turn-around time of 7 hours, pot scrap loss of 5 kg, top & tail loss of 5.8 kg and crystallization loss of 8%.

Further, it assumes that for a 50% Siemens chunk/50% FBR Granular blend, the crucible load for each puller cycle is 123.75 kg with a loading time of 42.84 minutes, melting time of 8 hours, pulling time of 54 hours, turn-around time of 7 hours, pot scrap loss of 5 kg, top & tail loss of 5.8 kg and crystallization loss of 8%. Table 3 summarizes the assumptions used for the model.

Plant	100% Siemens Blend	50% Siemens/ 50% Granular Blend
300 mono pullers	Crucible load = 95.7 kg	Crucible load = 123.75 kg
90 kg crucibles	Loading time = 72.65 min	Loading time = 42.84 min
156 x 156 mm ingots	Melting time = 6 hours	Melting time = 8 hours
90 hr/year puller maintenance	Pulling time = 48 hours	Pulling time = 54 hours
In-situ crucible loading	Turn-around time = 7 hours	Turn-around time = 7 hours
Full utilization	Pot scrap loss = 5 kg	Pot scrap loss = 5 kg
$1,000/pull consumables	Top & tail loss = 5.8 kg	Top & tail loss = 5.8 kg
No top-off or recharge	Crystallization loss = 8%	Crystallization loss = 8%

Table 3. *Summary of Hypothetical Case Study Model Assumptions*

The resulting calculated benefits are that the total crucible loading time is reduced by 29,385 hours per year while productive tool time is increased by 71,281 hours, consumables cost are reduced by $8,962,709, total yieldable ingot is increased by 270,496 kilograms and scrap/ remelt is reduced by 81,693 kilograms. These results are summarized in Table 4. Further detail regarding the model is included in Appendix B.

Blend	Loading Time (hr/yr)	Productive Tool Time (hr/yr)	Consumables ($/yr)	Yielded Ingot (kg/yr)	Scrap/Remelt (kg/yr)
100% Siemens	56,024	1,943,436	$46,272,288	3,574,257	854,001
50% Siemens/ 50% Granular	26,639	2,014,717	$37,309,579	3,844,752	772,308
Benefit	↓ 29,385	↑ 71,281	↓ $8,962,709	↑ 270,496	↓ 81,693

Table 4. *Summary of Benefits of a 50% Siemens Chunk/50% FBR Granular Blend vs. a 100% Siemens Blend – Plant Scale Hypothetical Case*

Conclusion

The results of a crucible loading test conducted by REC Silicon that demonstrates that the use of a 50% Siemens chunk/50% FBR Granular blend increases initial crucible charge weight by 29.3% while reducing loading time by 41.0% when compared to a 100% Siemens chunk blend. A model was described which demonstrates that the use of a 50% Siemens chunk/50% FBR Granular blend at the plant scale will result in an increase of yieldable ingot of several hundred tons per year, while reducing consumables cost by several million dollars and providing additional benefits when compared to a 100% Siemens chunk blend. Significant additional benefit can be gained by using FBR Granular for crucible top-off and recharge. Further investigations will be undertaken to quantify those benefits.

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Appendix A – Crucible Loading Test Report

Experimental Design

A standard 60 kg quartz CZ crucible typically used by monocrystalline ingot manufacturers was filled with different blends of Siemens chunk and FBR Granular polysilicon. During the filling process for each blend, the time to fill the crucible and the net weight was recorded. Measurements were made when the crucible was full, such that the load came level with the lip of the crucible and subsequently with a mound piled towards the center of the crucible that rose ~60 mm above the lip. Photographs were taken periodically during the crucible loading process to illustrate the filling sequence and the final filled crucible.

Prior to the loading tests the crucible was measured. A dimensional overlay drawing of the crucible is shown in Figure 2. The inside diameter measured 432 mm. The interior height from the lip to the lowest point of the dome measured 342 mm. The interior height from the lip to the cylinder/dome transition measured 240 mm. The weight of the crucible, including stand, measured 21.84 kg. The volume of the crucible was verified to be slightly greater than 44,000 cm^3 by filling with water to a height ~10 mm from the top.

Parameter	Value	Units
Rating	60	kg
Weight w/stand	21.84	kg
Interior Diameter	432	mm
Interior height to bottom	342	mm
Interior height to cylinder/dome transition	240	mm
Volume (to ~10 mm from top)	>44,000	cm^3

Table 5. *Test Crucible Measurements*

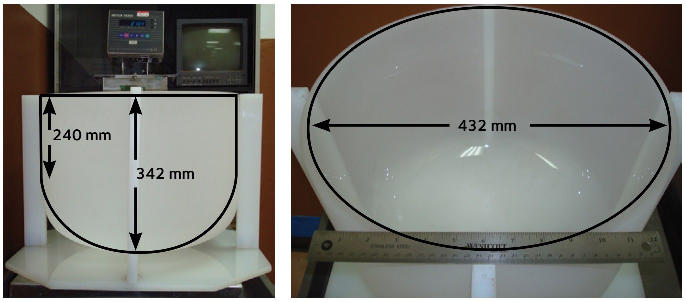

Figure 2. *Test Crucible with Dimensional Overlay*

Test 1 – 100% FBR Granular

The first blend tested was 100% FBR Granular. The crucible was filled level in ~2 minutes and 30 seconds with a charge weight of 66.37 kg . The crucible was filled with a mound in 2 minutes and 44 seconds with a charge weight of 71.91 kg.

	Time to Fill	Charge Weight
Level	~2 min 30 sec	66.37 kg
w/ Mound	2 min 44 sec	71.91 kg

Table 6. *Test 1 (100% FBR Granular) Filling Results*

Figure 3. *Test 1 (100% FBR Granular) Filling Sequence*

Test 2 – 100% Siemens Chunk

The second blend tested was 100% Siemens chunk. The crucible was filled level in 48 minutes and 26 seconds with a charge weight of 63.82 kg. The crucible was filled with a mound in 50 minutes and 42 seconds with a charge weight of 67.09 kg.

	Time to Fill	Charge Weight
Level	48 min 26 sec	63.82 kg
w/ Mound	50 min 42 sec	67.09 kg

Table 7. *Test 2 (100% Siemens Chunk) Filling Results*

Figure 4. *Test 2 (100% Siemens Chunk) Filling Sequence*

Test 3 – 58% Siemens Chunk/42% FBR Granular

The third blend tested was 58% Siemens chunk and 42% FBR Granular. The crucible was filled level in 37 minutes and 2 seconds with a charge weight of 82.04 kg. The crucible was not filled with a mound during this test.

	Time to Fill	Charge Weight
Level	37 min 2 sec	82.04 kg
w/ Mound	NA	NA

Table 8. *Test 3 (58% Siemens Chunk/42% FBR Granular) Filling Results*

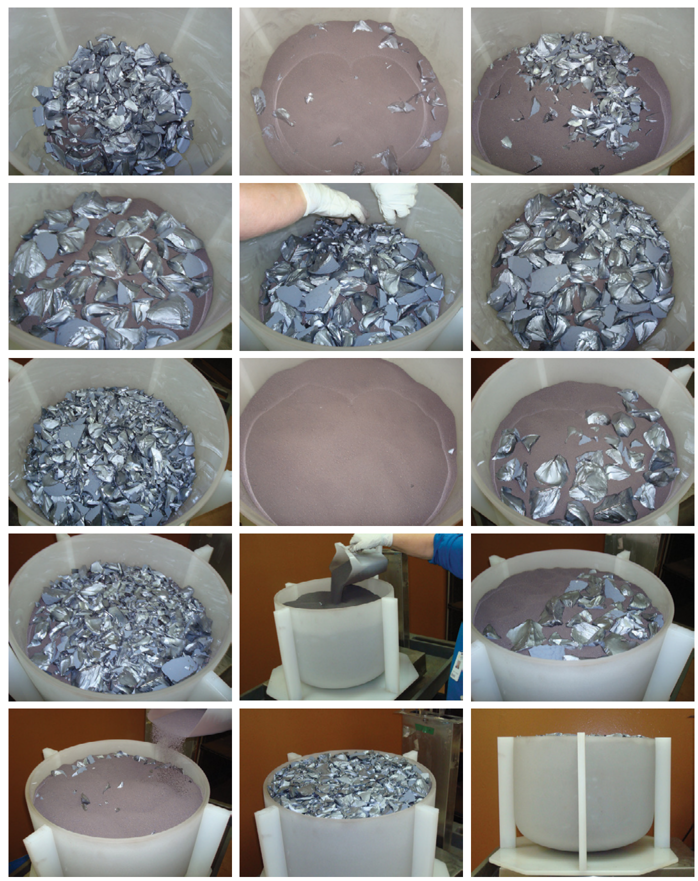

Figure 5. *Test 3 (58% Siemens Chunk/42% FBR Granular) Filling Sequence*

Test 4 – 50% Siemens Chunk/50% FBR Granular

The fourth blend tested was 50% Siemens chunk and 50% FBR Granular. The crucible was filled level in 28 minutes and 34 seconds with a charge weight of 82.54 kg. The crucible was filled with a mound in 31 minutes and 1 second with a charge weight of 84.10 kg.

	Time to Fill	Charge Weight
Level	28 min 34 sec	82.54 kg
w/ Mound	31 min 1 sec	84.10 kg

Table 9. *Test 4 (50% Siemens Chunk/50% FBR Granular) Filling Results*

Figure 6. *Test 4 (50% Siemens Chunk/50% FBR Granular) Filling Sequence*

Appendix B – Hypothetical Case Study Model Details

Plant	100% Siemens Blend	50% Siemens/ 50% FBR Granular Blend
300 mono-pullers	Crucible load = 95.7 kg	Crucible load = 123.75 kg
90 kg crucibles	Loading time = 72.65 min	Loading time = 42.84 min
156 x 156 mm ingots	Melting time = 6 hours	Melting time = 8 hours
90 hr/year puller maintenance	Pulling time = 48 hours	Pulling time = 54 hours
In-situ crucible loading	Turn-around time = 7 hours	Turn-around time = 7 hours
Full utilization	Pot scrap loss = 5 kg	Pot scrap loss = 5 kg
$1,000/pull consumables	Top & tail loss = 5.8 kg	Top & tail loss = 5.8 kg
No top-off or recharge	Crystallization loss = 8%	Crystallization loss = 8%

Table 10. *Hypothetical Case Study Model Assumptions*

Parameter	Units	100% Siemens Blend	50% Siemens/ 50% FBR Granular Blend
hr/year	hr/year	8,760	8,760
min/year	min/year	525,600	525,600
Pullers	Units	300	300
Crucible rating	kg	90	90
Puller maintenance	hr/year	90	90
Puller maintenance	min/year	5,400	5,400
Consumables	$/cycle	$1,000.00	$1,000.00
Crucible load	kg	95.7	123.75
Crucible loading time	min	72.65	42.84
In-Situ loading	Y/N	Y	Y
Melting time/cycle	hr	6	8
Melting time/cycle	min	360	480
Pulling time/cycle	hr	42	54
Pulling time/cycle	min	2,520	3,240
Turn-around time/cycle	hr	7	7
Turn-around time/cycle	min	420	420
Pot scrap loss	kg	5	5
Top & tail loss	kg	5.8	5.8
Crystallization loss	%	8%	8%

Table 11. *Hypothetical Case Study Model Inputs*

Parameter	Units	100% Siemens Blend	50% Siemens/ 50% FBR Granular Blend	Benefit
Puller cycle time	min	3,373	4,183	(810.2)
Puller cycles/yr	cycles/yr	154.24	124.37	(29.88)
Puller loading time	min/yr	11,204.83	5,327.81	5,877.0
Puller loading time	hr/yr	186.75	88.80	98.0
Plant loading time	hr/yr	56,024.17	26,639.04	**29,385.1**
Puller productive tool time	min	388,687.22	402,943.45	14,256.2
Puller productive tool time	hr	6,478.12	6,715.72	237.6
Plant productive tool time	hr	1,943,436.09	2,014,717.27	**71,281.2**
Puller consumables	$/yr	$154,240.96	$124,365.26	$29,875.70
Plant consumables	$/yr	$46,272,287.77	$37,309,579.14	**$8,962,708.64**
Puller poly processed	kg/yr	14,760.86	15,390.20	629.3
Plant poly processed	kg/yr	4,428,257.94	4,617,060.42	188,802.5
Puller yielded ingot	kg/yr	11,914.19	12,815.84	901.7
Plant yielded ingot	kg/yr	3,574,256.60	3,844,752.13	**270,495.5**
Puller scrap/remelt	kg/yr	2,846.67	2,574.36	272.3
Plant scrap/remelt	kg/yr	854,001.34	772,308.29	**81,693.1**

Table 12. *Hypothetical Case Study Model Outputs*

REC Silicon is a leading producer of advanced silicon materials, delivering high-purity polysilicon and silane gas to the solar and electronics industries worldwide. High-purity Signature Silane® gas (SiH^4) is central to the quality and consistency of all the company's materials. The company combines 25 years' experience and proprietary technology with the needs of its customers to provide value-added raw materials which are used to manufacture solar modules and silicon wafers. REC Silicon is the world's largest silane gas producer and one of the world's largest polysilicon manufacturers, with a capacity of more than 20,000 MT of polysilicon and 29,000 MT of silane gas annually from two US-based manufacturing plants. Listed on the Oslo Stock Exchange (ticker: REC), the company is headquartered in Moses Lake, Washington and employs 800 people.

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