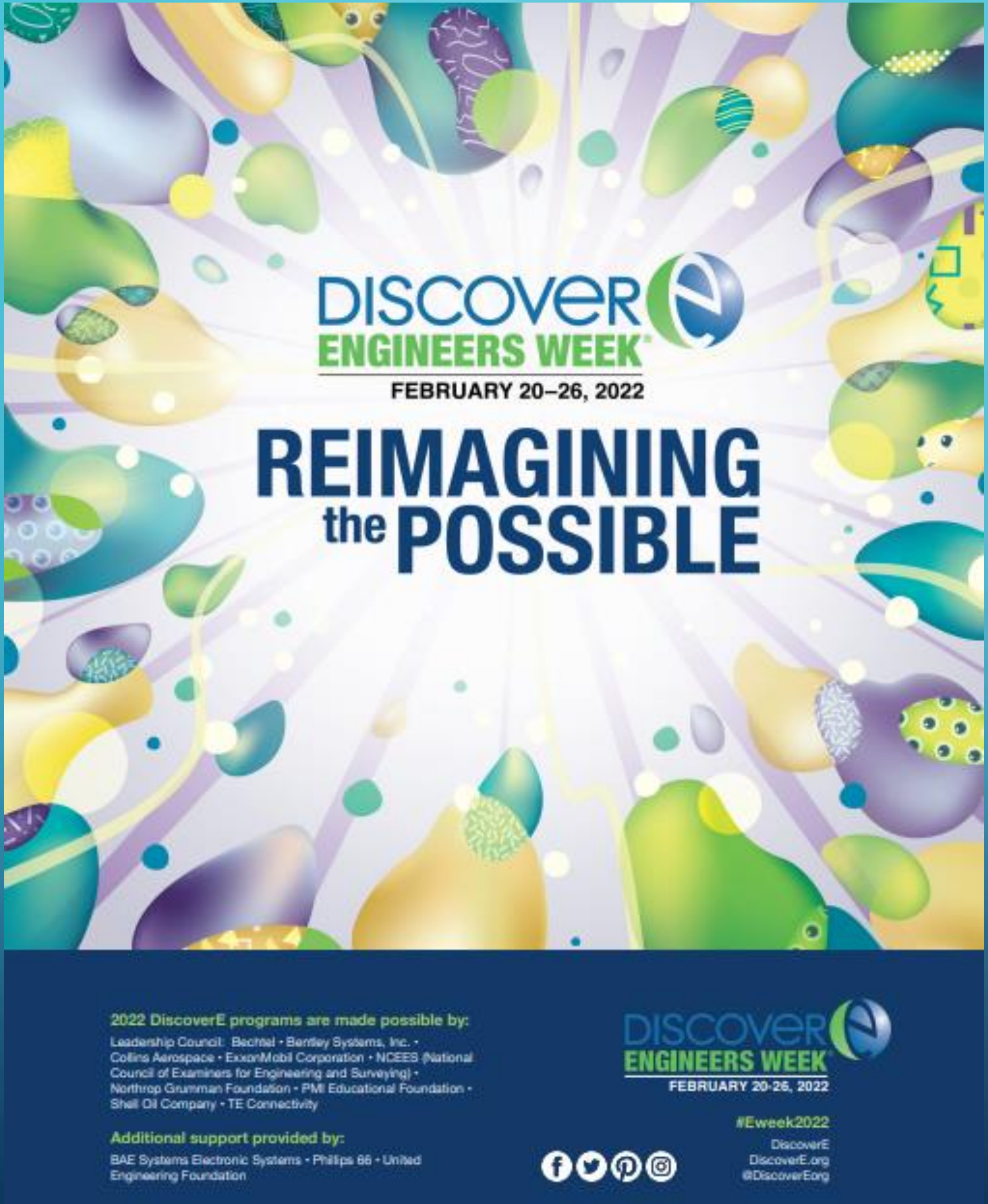

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ENGINEERS WEEK

FEBRUARY 20–26, 2022

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HSC HEMLOCK SEMICONDUCTOR

14
Si
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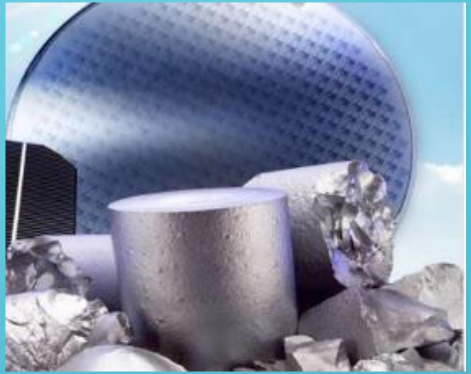


Intel Corporation

intel®

WHERE WILL THE INTEL OHIO CHIP PLANT GET THEIR PURE SI?

AICHE CLEVELAND SECTION, FEBRUARY 24, 2022 MEETING

PRESENTED BY: JOSEPH YURKO, PE & AICHE NEWSLETTER EDITOR
FORMER HSC PHARO III & IV CVD RECOVERY PROCESS LEAD
1998 MK & HSC TEAM ENGINEERING EXCELLENCE AWARD

WHY RAISE THIS QUESTION?

- $20 billion will be invested in Ohio for two new Intel Chip Manufacturing Factories built in New Albany, Liking County, Ohio (west of Columbus)
- The Intel Chip Factories will add 7,000 construction jobs over the next several years building the facilities
- The Intel Chip Factories will add 3,000 employees to operate the two factories.
- The average annual pay per Intel Chip Factory employee will be $135,000

Ref.: The Plain Dealer, Newspaper 22Jan2022

OHIO

'This is a great day in Ohio history'

WHY CHOOSE HEMLOCK SEMICONDUCTOR CORPORATION?

- HSC was founded in 1961 and was owned by Dow Corning Corporation, DCC
- DCC was a joint venture between Dow Chemical and Corning Class
- HSC now produces 36,000 tons per year of pure 9N Silicon (99.999999999% pure Poly-Si)
- In 2016 a DCC venture between Dow and Corning was dissolved after 73 years
- HSC was sold to Corning Inc. (80%) and Shin-Etsu Handoti (20%) in 2016
- HSC built a $1.2 B plant in Clarksville, Tennessee in 2012 that closed in 2014 due to Poly-Si global prices
- HSC will receive high purity quartz rock and process it into high-purity polysilicon cut rods, chunk, chip, and fines in a variety of customer friendly options to meet their crucible loading requirements
- My story begins in 1997 with the MK & HSC Pharo III & IV Projects that doubled the size of the facility shown below as it was in 1998 (Pharo III Project Construction Completed)

HSC PHARO III PROJECT PLAN

- Continental Air transportation wheels up 7AM from CLE to Midland, MI
- We depart Cleveland Hopkins Airport on a 19 seat twin prop plane
- 4 to 8 of the passengers were from MK and we were known as Road Warriors
- Passengers walked onto the tarmac to the plane, and placed their luggage under left wing of airplane
- Passengers boarded airplane as the pilot and co-pilot loaded luggage
- Before starting engines, the pilot opened his window to yell, “all clear!”
- Continental airplane arrived at the Tri-City Airport in Michigan at 1 of 2 gates (Midland, Saginaw, and Bay City area airport)

HSC 1997 PHARO III PROJECT PLAN

- HSC Operating Plant located in Hemlock, MI
- HSC & Pharo III Project owned & engineered by Dow Corning Corporation
- Dow Corning Corporation (DCC) located in Midland, MI
- DCC provided Engineering Maintenance Technology Network (EMTN)
- DCC provided PROFS communication network for text messaging progress reports (dashboard approach: Green, Items going well; Yellow, Concerns; Red, Problem)
- DCC hosted all P&ID reviews & Process Hazard Analysis (HAZOP)
- Morrison Knudsen Corporation (MKC) was engineering contractor
- MKC ran engineering process simulations on both ChemCad and Aspen
- MKC did most engineering work in Cleveland, OH, had monthly project meetings in Midland, MI, and HSC construction site visits in Hemlock, MI

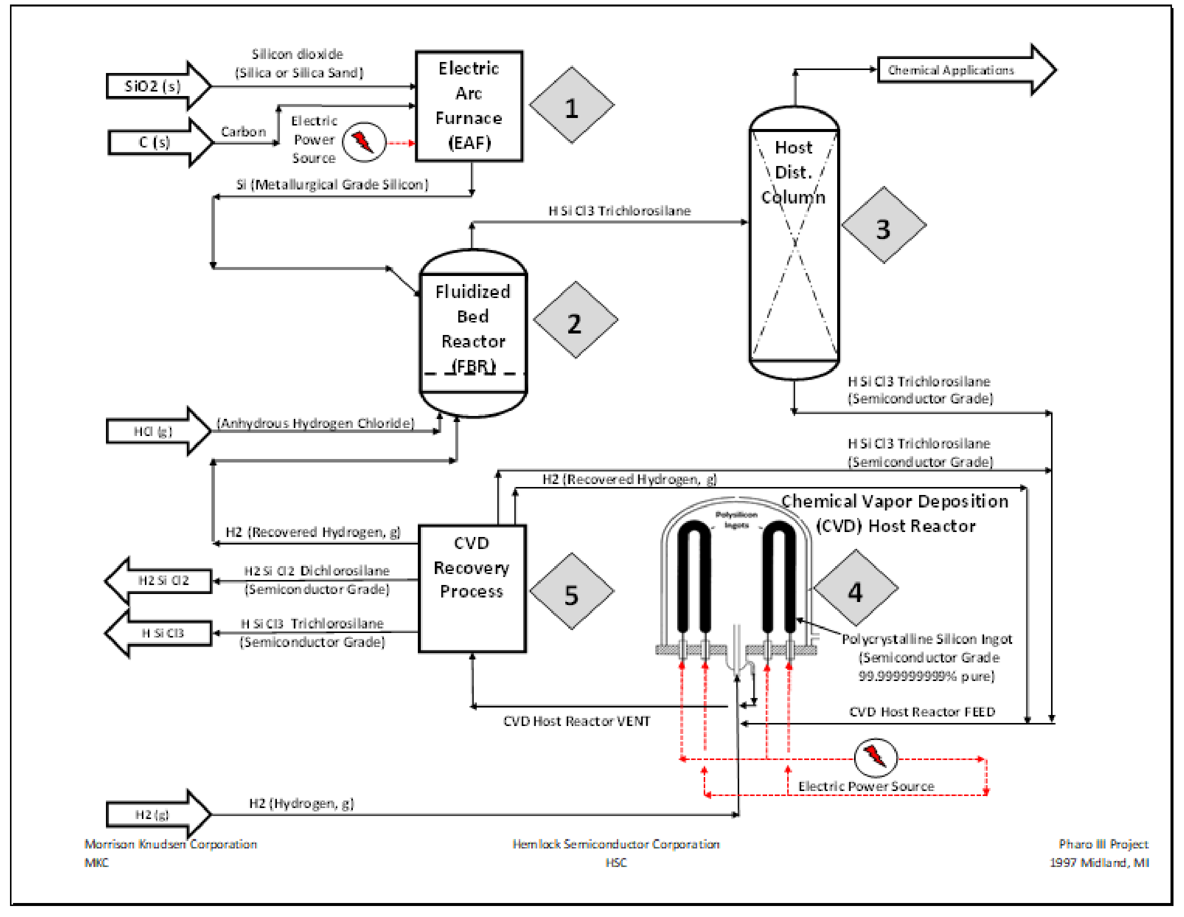
★ HSC Polysilicon Process is proprietary and the following presentation is based on two technically accurate papers that closely resemble the HSC Polysilicon Process

Ref.: https://www.hscpoly.com/polysilicon.html

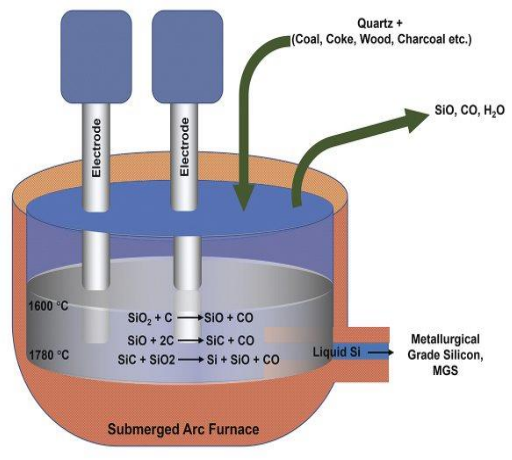
PROCESS AREAS OF HSC MANUFACTURING

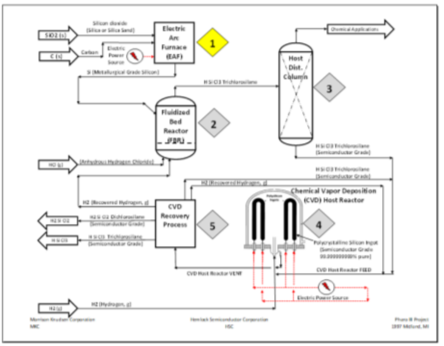
1. Electric Arc Furnace (EAF)
2. Fluidized Bed Reactor (FBR)
3. Host Distillation
4. Chemical Vapor Deposition (CVD) Reactor
5. CVD Recovery Process

Ref.: https://www.hscpoly.com/polysilicon.html

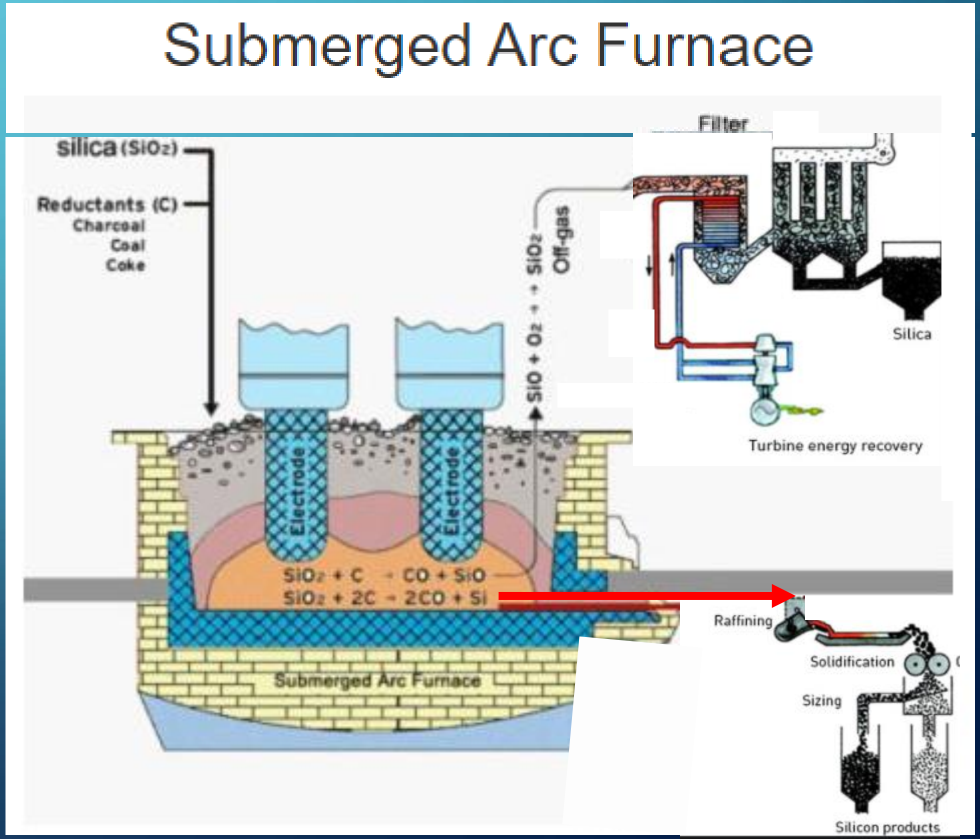


PROCESS AREA # 1: ELECTRIC ARC FURNACE (EAF) SUBMERGED



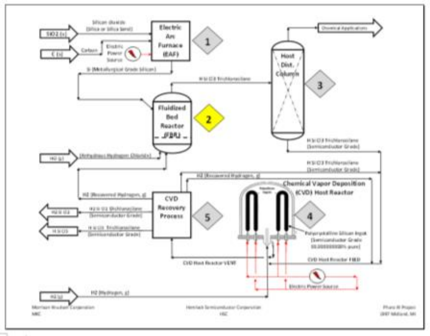


- EAF Reactants: C and SiO_2 (silicon dioxide, quartz, silica, pure silica, and silica sand)
- EAF Products: Si and CO (with impurities)
- Electric Arc Furnace Reactions:
    - $\mathbf{SiO_2} + \mathbf{2\ C} \rightarrow \mathbf{Si} + 2\ CO$ (1,780.°C or 3,236.°F)
    - $SiO_2 + C \rightarrow SiO + CO$
    - $SiO + O_2 \rightarrow \rightarrow SiO_2$ (Off Gas)
    - Where the Si is a metallurgical grade silicon that is collected as molten Si, cooled, and milled into granules
    - With SiO_2 Off Gas filtered in a by-product Collector

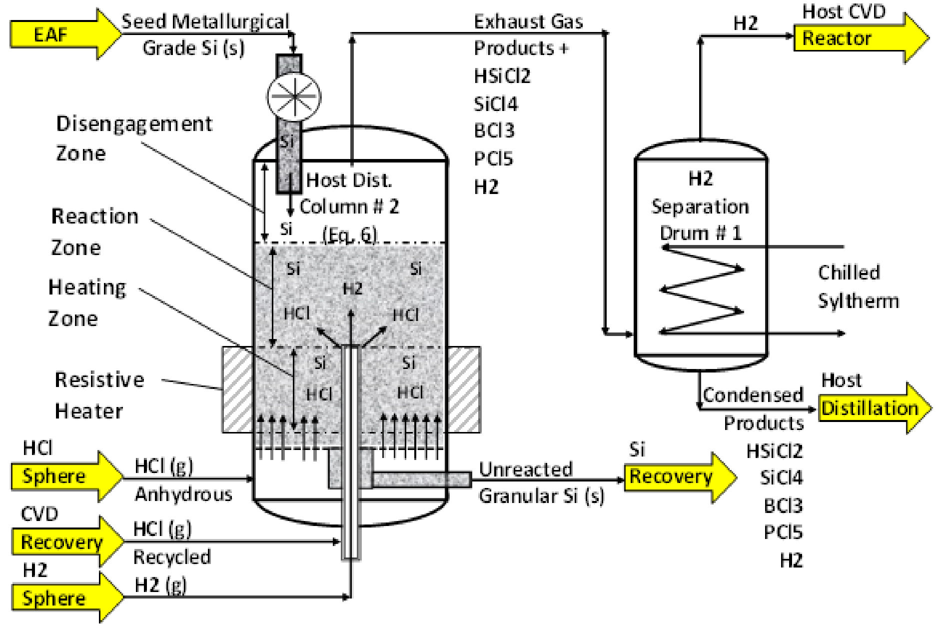


Ref.: https://www.hscpoly.com/polysilicon.html

PROCESS AREA # 2: FLUIDIZED BED REACTOR (FBR)



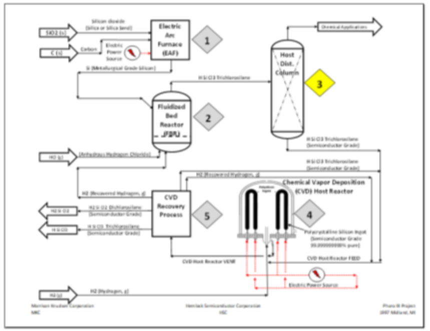
- FBR Reactants: Metallurgical Grade Si (s) and HCl (g, anhydrous)
- FBR Products: Trichlorosilane (TCS, $HSiCl_3$), Tetrachlorosilane (TET, $SiCl_4$), Hydrogen (H_2), Boron Trichloride (BCl_3), and Phosphate Pentachloride (PCl_5)
- FBR Events
  - Solid Metallurgical Grade Si is fed into the reactor
  - HCl (g, anhydrous) is fed through the bottom of the reactor
  - HCl (g, anhydrous) reacts with Si to form silicon chlorides
  - Vapor products are collected from the top of the reactor
  - Unreacted Si (s) removed through the bottom of the reactor
- Fluidized Bed Reactor Reaction:
- $HCl + Si \rightarrow HSiCl_3 + SiCl_4 + CO + H_2 + BCl_3 + PCl_5$



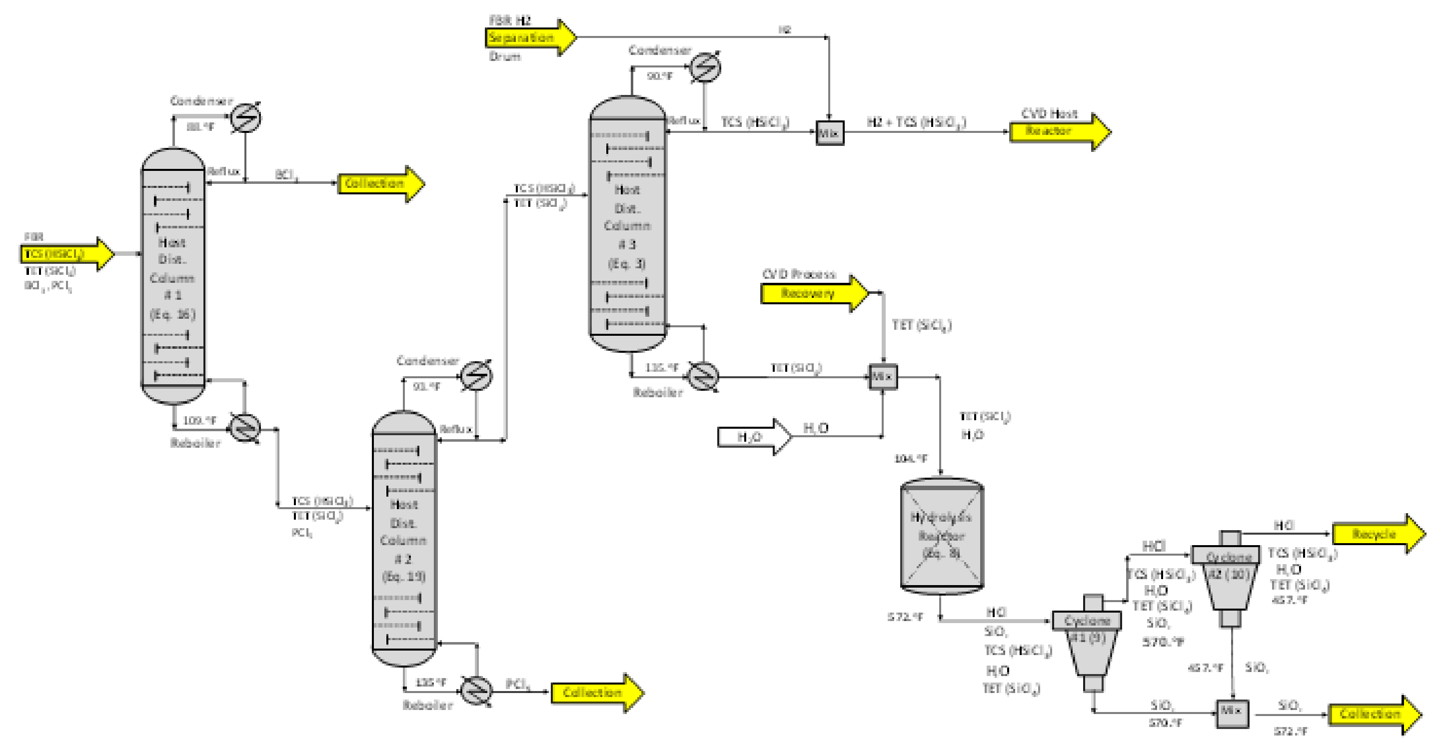
Fluidized Bed Reactor (FBR)

- Ref.: Production of Polysilicon using a Modified Siemens Process: Geng and Yu, 11May2011, ChemCAD 6.0.1

PROCESS AREA # 3: HOST DISTILLATION COLUMNS

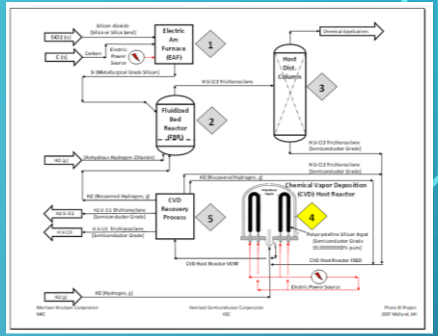


- Dist. Column # 1 (16) 70’ Tall, 8’ D
  - Sieve Plate Tray Column Design, 24 Trays
  - Feed: **TCS** ($HSiCl_3$), **TET** ($SiCl_4$), **BCl_3** , **PCl_5**
  - Top Distillate (88.°F): Boron Trichloride, **BCl_3**
  - Bottoms (109.°F): **TCS** ($HSiCl_3$), **TET** ($SiCl_4$), **PCl_5**
- Dist. Column # 2 (19) 70’ Tall, 8’ D
  - Sieve Plate Tray Column Design, 24 Trays
  - Feed: **TCS ($HSiCl_3$)**, **TET ($SiCl_4$)**, **PCl_5**
  - Top Distillate (93.°F): **TCS** ($HSiCl_3$), **TET** ($SiCl_4$)
  - Bottoms (135.°F): Phosphate Pentachloride, **PCl_5**
- Dist. Column # 3 (3) 55’ Tall, 8’ D
  - Sieve Plate Tray Column Design, 20 Trays
  - Feed: **TCS** ($HSiCl_3$), **TET** ($SiCl_4$)
  - Top Distillate (90.°F): **TCS** ($HSiCl_3$)
  - Bottoms (135.°F) : **TET** ($SiCl_4$)
- Hydrolysis Reactor
  - Packed Bed Design
  - Reactants: **Water (H_2O)**, **TET ($SiCl_4$)**
  - Hydrolysis Reaction (2012.°F) :
    - $\mathbf{SiCl_4 + 2\,H_2O \rightarrow SiO_2 + 4\,HCl}$
    - $SiCl_4 + HCl \rightarrow SiO_2 + \mathbf{HSiCl_3} + SiCl_4$
  - Products: **SiO_2 , HCl, TET ($SiCl_4$), TCS ($HSiCl_3$)**

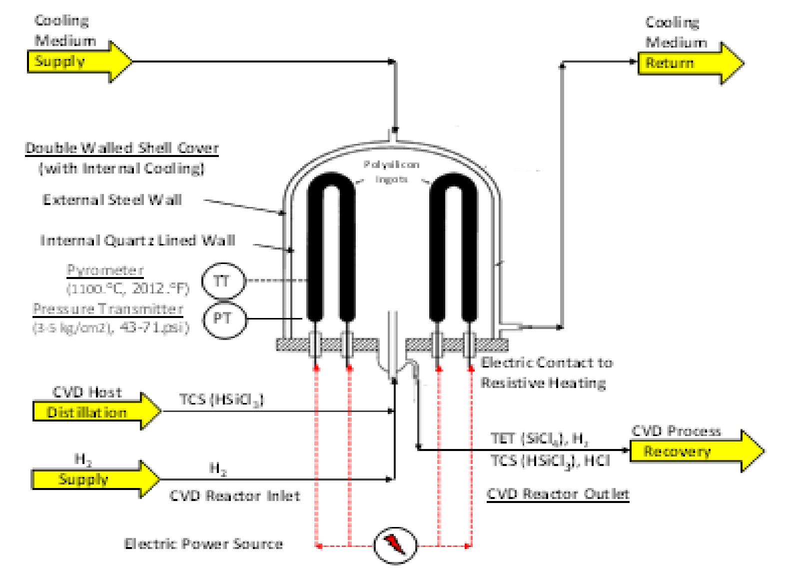


Ref.: Production of Polysilicon using a Modified Siemens Process: Geng and Yu, 11May2011, ChemCAD 6.0.1

PROCESS AREA # 4: CHEMICAL VAPOR DEPOSITION (CVD) REACTOR



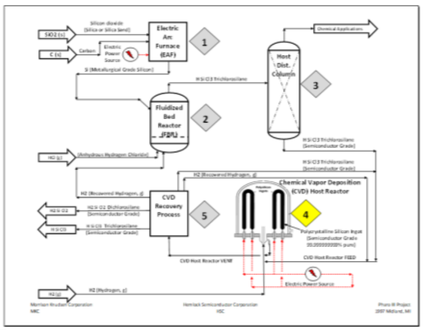
- Production of a Poly-Si ingot is by Siemens Process of decomposing TCS by Chemical Vapor Deposition onto slim hot Tungsten Rods in a double walled (liquid cooled) steel bell jar reactor
- Reactants: **TCS ($HSiCl_3$), H_2** (g)
- Products: 99.999999999% (9N) Pure Poly-**Si** Ingots
- Reaction: $\mathbf{H_2 + 3\ HSiCl_3 \rightarrow 2\ Si + 5\ HCl + SiCl_4}$
- Reaction at 1050.℃ to 1100.℃ or 2012°F
- Set-up: a Tungsten (W) rod with an inverted “U” shape (for vaporized Si nucleation) is attached to the CVD Reactor base
- Electrical Power Resistive Heating of W Rods: 45 kWh/kg Si
- CVD Reactor internal Pressure: 3-5 kg/cm2 (45-71. psi)
- CVD Reactor Operating Temperature: at 1100°C (2012°F)
- Time for complete Poly-Si deposition: 3-5 days
- Reactor Double Wall Shell has liquid cooled temperature control
- CVD Reactor System Automation to be detailed later



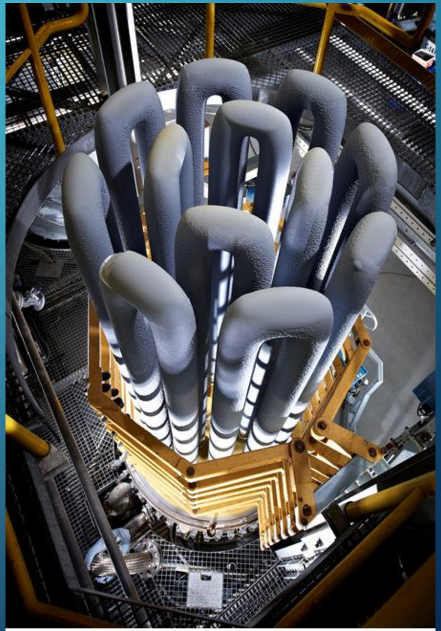
Chemical Vapor Deposition (CVD) Reactor

Ref.: Design & Process Control of Siemens Polysilicon CVD Reactor: Kurnool, Andhra, Pradesh, 12Dec2015

PROCESS AREA # 4: CHEMICAL VAPOR DEPOSITION (CVD) REACTOR



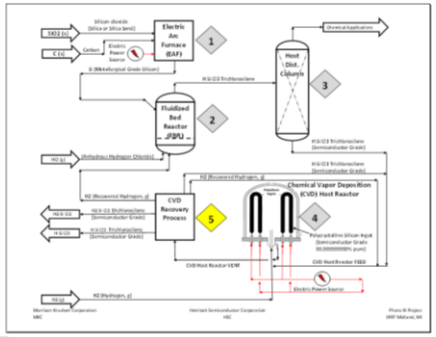
- Silicon Ingot growing rate: up to 1.9 mm/h
- Silicon deposition rate: 30 kg/h
- Molar ratio H2/TCS: 3.5 mol/mol
- Total silicon deposition per run: up to 3,700 kg
- Specific energy consumption: 45 kWh/kg Si
- Specific energy recuperation: 35 kWh/kg Si
- Up to 3,200 mm Ingot length (126 inches, 11 feet)
- Up to 180 mm Ingot diameter (7.09 inches)
- Up to 3,700 kg (8,140. lbs.) polysilicon / run.



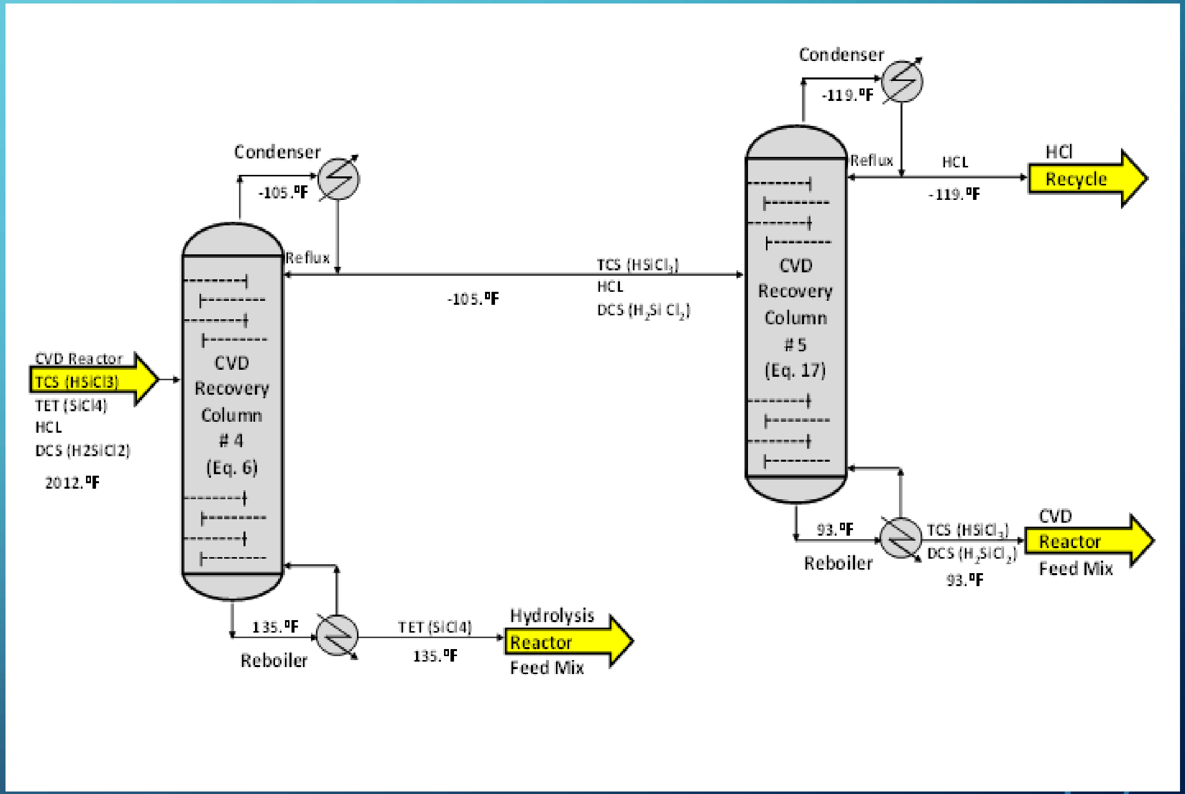
Polysilicon rods after CVD-Process

Ref.: https://silicon-products-gmbh.com/deposition-reactor-siemens-reactor

PROCESS AREA # 5:
CVD PROCESS RECOVERY

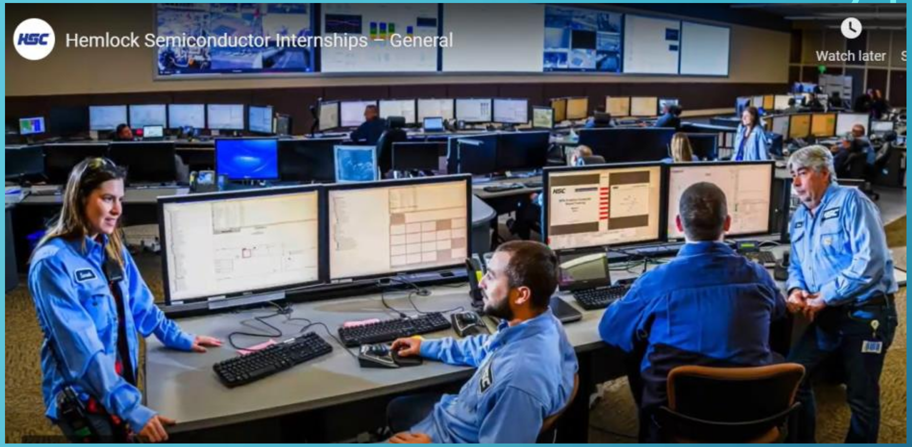


- Column # 4 (6) 55’ tall, 8’ Diameter
  - Sieve Plate Tray Column Design, 24 Trays
  - Feed: **TCS ($HSiCl_3$), TET ($SiCl_4$), HCL, DCS ($H_2Si\ Cl_2$)**
  - Distillate (118.°F): **TCS ($HSiCl_3$), HCL, DCS ($H_2Si\ Cl_2$)**
    Condenser had hot Syltherm Utility
  - Bottoms (138.°F): **TET ($SiCl_4$)**
- Column # 5 (17) 40’ tall, 6.5’ Diameter
  - Sieve Plate Tray Column Design, 12 Trays
  - Feed: **TCS ($HSiCl_3$), HCL, DCS ($H_2Si\ Cl_2$)**
  - Distillate (-119.°F): **HCl**
    Condenser had very cold Syltherm Utility
  - Bottoms (84.°F): **TCS ($HSiCl_3$), DCS ($H_2Si\ Cl_2$)**



Ref.: Production of Polysilicon using a Modified Siemens Process: Geng and Yu, 11May2011, ChemCAD 6.0.1

PROCESS AREA:
CVD REACTOR SYSTEM AUTOMATION



- Production of a Si ingot is by Siemens Process of decomposing TCS by Chemical Vapor Deposition onto slim hot Tungsten Rods
- Systems Automation for the CVD Reaction unit operation may be represented by a Graphical User Interface (GUI). It is the primary tool for distributed automation on an electric utility operating with SCADA/EMS
- The Supervisory Control and Data Acquisition (SCADA) system stores information from the remotely located data collection sensors and transducers to support control of equipment, devices and automated functions as well as the Emergency Management System (EMS)
- The proposed hardware architecture for monitoring and control of the sequential processes of polysilicon CVD reactor are in Fig. 1
- Hydrogen gas is fed with TCS gas into the CVD Reactor depositing Si onto the hot tungsten rod based on the following reaction equation:
  $H_2 + 3\,HSiCl_3 \rightarrow 2\,Si + 5\,HCl + SiCl_4$ (at 1050.°C to 1100.°C or 2012°F**)**
- Polysilicon, Si, deposits onto the hot tungsten rod surface for 4 to 5 days increasing the Ingot growth in diameter from 3mm to 100mm (4 in.) or 150mm (6 in.)
- This is electrically powered by an incomer panel supplying a 3 phase 11kV main stepped down to 100-300 V at 5000 A by an auto-main transformer with On-Load Tap Changer (OLTC). Thyristor controls the load power by varying the firing angle.
- 3 pyrometers placed around the reactor sense filament glow temperatures from 600-1400.℃ and provide a 4-20 mA temperature control signal

Ref.: Design & Process Control of Siemens Polysilicon CVD Reactor: Kurnool, Andhra, Pradesh, 12Dec2015

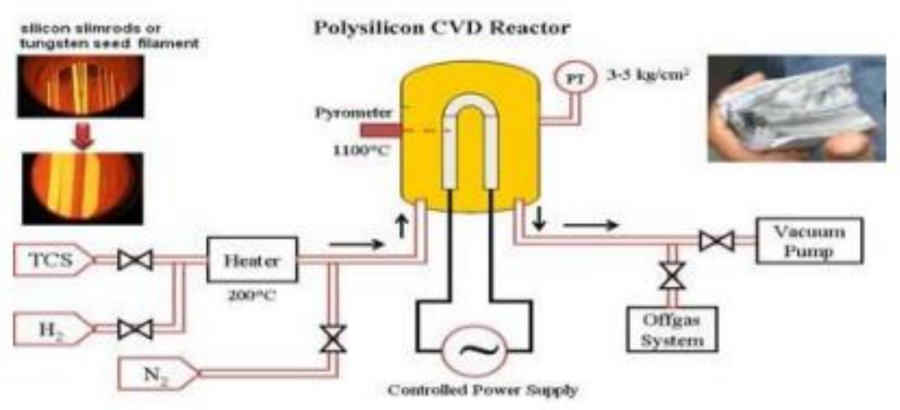


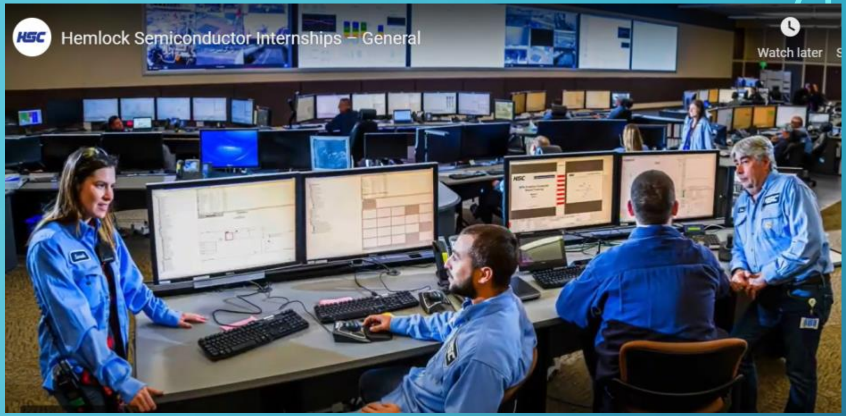
Fig. 1. Block diagram of poly -silicon CVD reactor [7], [8]

- Temperature control of cooling supply to the reactor double wall shell is done with flow switch valves
- Reactor Pressure transmitters range from -14.2 to 142. psi
- Feedback control technique is applied to Si ingot growth
- ★ The software control package for this situation is National Instruments LabVIEW 8.6 version and MATLab 7.5 software tools for an effective proposed control technique

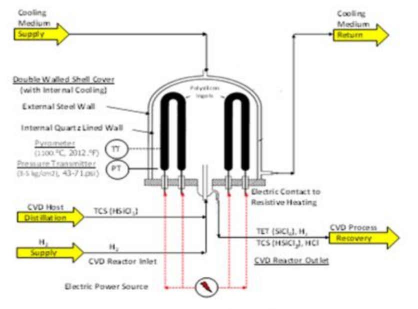
PROCESS AREA:

CVD REACTOR SYSTEM AUTOMATION:

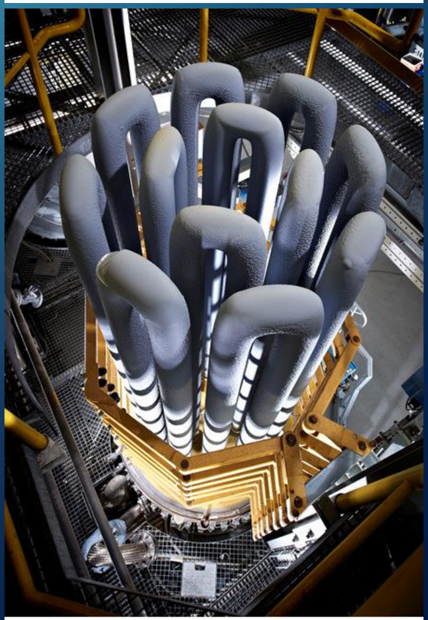
CHALLENGES OF A POLYSILICON CVD REACTOR



- Development of reactor sequence of operation
  - Reactor evacuation (purity level = 10N) and leak test (hold 1E-5 torr or 2E-7 psi) with supervisory check list ensuring we have leak-free status
  - TCS and H2 feed rate gas ratios are scheduled to achieve the reaction thermal kinetics are ensured with a closed loop control system at the optimum temperature control range
  - Optimum Temperature control range is at 1050.℃ to 1100.℃ (2012°F)
    - If Temperatures decrease then the optimum ingot growth rate takes longer to complete
    - If Temperatures increase then the surface of polysilicon softens losing stability causing filament fracture of the ingot
    - A state model is designed to realize the plant dynamics at different temperatures to obtain the transient and frequency response with respect to the plant dimensions
    - The HMI designed handles and alarms the user regarding the likelihood of fault tree tolerance and remedies to give a multi-layer protection to the events of Siemens CVD System by making it compliant with required industrial standards
  - Shutdown process and ingot removal
- Multi-Input and Multi-Output (MIMO) System
- Thermally coupled filaments/ingots with radiation heat transfer
- Continually increased ingot diameter with thermal mass
- Constantly changed gas mass and their stream ratios
- Thermal runaway causes increase in current, temperature and decrease in resistivity



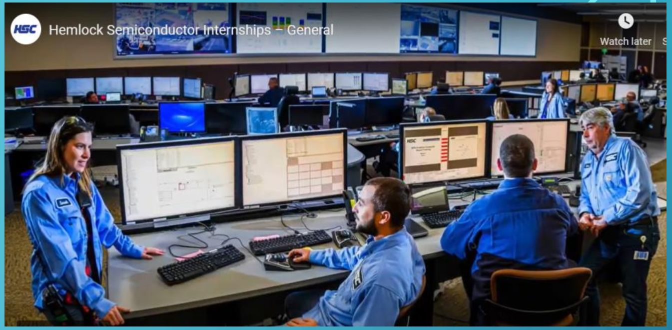
Chemical Vapor Deposition (CVD) Reactor



Polysilicon rods after CVD-Process

Ref.: Design & Process Control of Siemens Polysilicon CVD Reactor: Kurnool, Andhra, Pradesh, 12Dec2015

PROCESS AREA:
CVD REACTOR SYSTEM AUTOMATION:
CVD REACTOR PROCESS SAFETY AND EMERGENCY HANDLING



- Process and instrumentation dynamics are the key considerations with the multi-layered protection for system analysis
- Each layer of protection groups an equipment and/or human activity which address an emergency situation to be informed to the community with an engineering approach to control hazard
- This decision required for the measurement of Safety Instrumented System (SIS) performance is made acceptable with industrial standards to reach the assignment of target Safety Integrity Level (SIL) with the extension of a Process Hazard Analysis (PHA) to mitigate risk associated with each level of CVD Reactor operation.
- For a safe circuit operation of a Polysilicon CVD Reactor follow the standard ANSI/ISA S5.1-1984(R1992) for the design phase of the thermal plant for quick and reliable information about process analysis and control of equipment
- Electrical design development follows SEMI S22-0706a standard for safe operation
- An umbrella standard, IEC d61508, for Industrial Electrical/Electronic & Programmable Electronic Safety Related Systems (E/E/PE SRS)

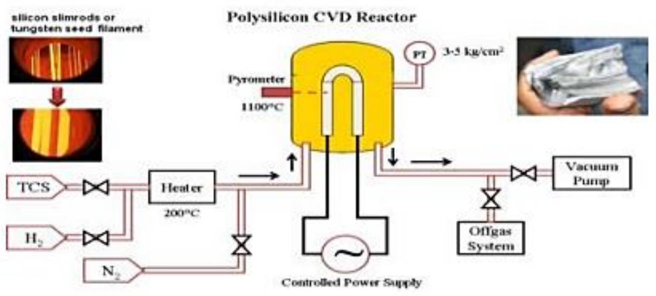
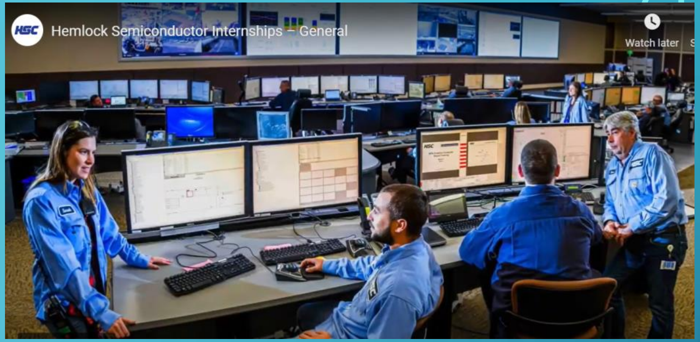


Fig. 1. Block diagram of poly -silicon CVD reactor [7], [8]

Ref.: Design & Process Control of Siemens Polysilicon CVD Reactor: Kurnool, Andhra, Pradesh, 12Dec2015

PROCESS AREA:
CVD REACTOR SYSTEM AUTOMATION:
CVD REACTOR PROCESS SAFETY AND EMERGENCY HANDLING



- Risk control in terms of likelihood and the severity of hazards are achieved qualitatively and quantitatively with PHA studies with assignment of Target Safety Integrity Levels (SIL) for Safety Instrument Functions (SIF)
- Quantitative risk analysis techniques such as Event Tree Analysis helped in easy identification of hazards and risks associated in the process by suggesting suitable remedies for elimination
- Qualitative techniques such as Hazard and Operability (HAZOP) studies and Failure Mode, Effects and Criticality Analysis (FMECA) were adopted to identify failed events and mitigate the process to safeguard the system prior to startup
- A Checklist verification of the systems/equipment is done to avoid hazards before the process startup (Reactor contents: H2 and HCl gas)
- Challenging failures: Power Control & Distribution Panel (i.e., over current, under current, earth fault, ground fault, and voltage fault protections), air cooling, and over pressure of equipment (heat exchanger, pump, valve, rectifier, and pyrometer)
- Shutdown failures: Power loss, power blink, instrument air, cooling water, tube rupture, thermal run-away reaction, quartz window breakage, malfunction of vacuum circuit breaker, reactor leak (HCl gas), and communication failure

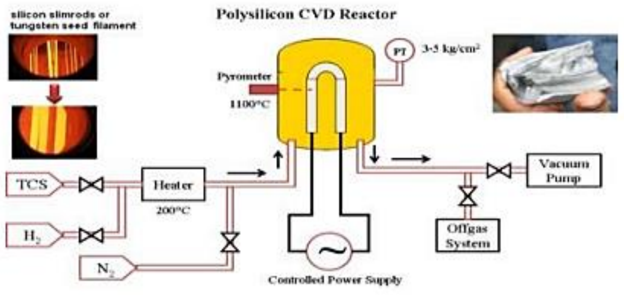


Fig. 1. Block diagram of poly -silicon CVD reactor [7], [8]

Ref.: Design & Process Control of Siemens Polysilicon CVD Reactor: Kurnool, Andhra, Pradesh, 12Dec2015

PROCESS AREA:
CVD REACTOR SYSTEM AUTOMATION:
CVD REACTOR SIMULATION RESULTS (PART 1 OF 7)

- Hardware simulation is developed using National Instrument LabVIEW8.6 for visualizing the sequential plant processes
- Reactor evacuation and its status were realized with its ideal and practical characteristics shown in Fig. 2
- Time required to evacuate air inside the reactor from an initial pressure Pi to a final pressure Pf is estimated as:
    - t = evacuation time (hrs)
    - S = average pump suction capacity (m3/hr)
    - Pa = air pressure in reactor at to (torr)
    - Pf = final pressure in reactor at t1 (torr)
    - d = diameter of reactor (n)
    - h = height of reactor (m)
    - v = volume of reactor (m3)

$$t = \left(\frac{v}{s}\right) \ln\left(\frac{P_a}{P_f}\right)$$

- Values in Table I are practical and real time values obtained during the test
- This process is iterated 2 or 3 times until the practical characteristics are identical to the ideal characteristics reaching the minor leak check point reading 1x10-5 torr

Ref.: Design & Process Control of Siemens Polysilicon CVD Reactor: Kurnool, Andhra, Pradesh, 12Dec201

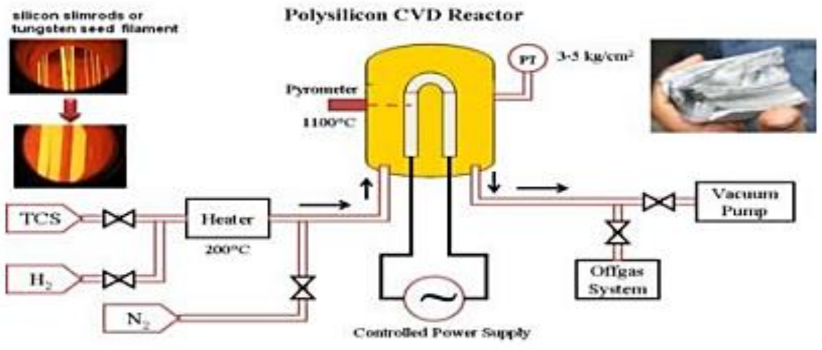


Fig. 1. Block diagram of poly -silicon CVD reactor [7], [8]

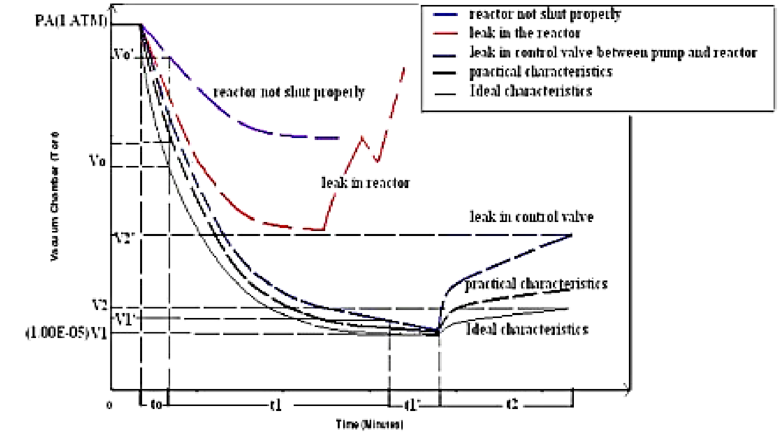
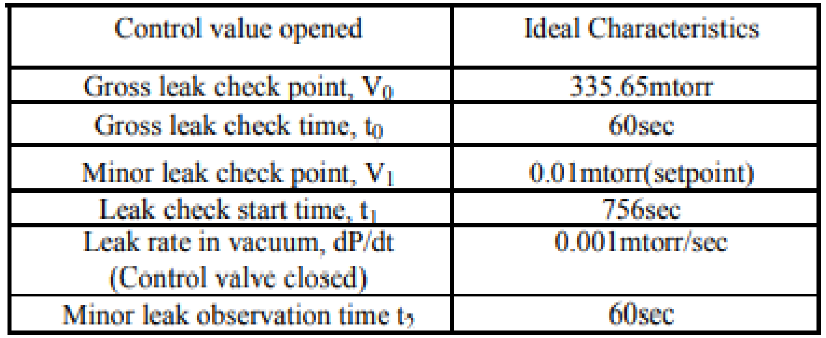


Fig. 2. Illustrates the characteristics of the Evacuation curve under different circumstances.

TABLE I VALUE OF CHECK POINTS



Control value opened	Ideal Characteristics
Gross leak check point, V_0	335.65mtorr
Gross leak check time, t_0	60sec
Minor leak check point, V_1	0.01mtorr(setpoint)
Leak check start time, t_1	756sec
Leak rate in vacuum, dP/dt (Control valve closed)	0.001mtorr/sec
Minor leak observation time t_5	60sec

PROCESS AREA:
CVD REACTOR SYSTEM AUTOMATION:
CVD REACTOR SIMULATION RESULTS (PART 2 OF 7)

- If test iterations prove the reactor is not leak free, then the cooling jacket is replaced and testing is repeated
- Process mimic, observation table and graph screens are shown in Fig. 3, 4 and 5
- After the start-up stage is verified with a leak test that is carried out with N2 and H2 flushing, the process starts with feed rate scheduling

Ref.: Design & Process Control of Siemens Polysilicon CVD Reactor: Kurnool, Andhra, Pradesh, 12Dec2015

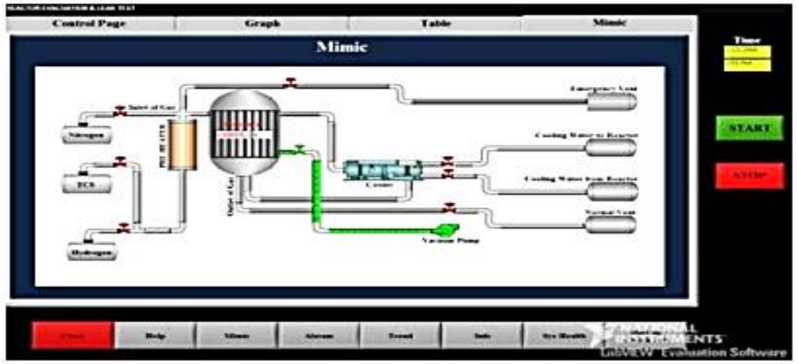


Fig. 3. Mimic page illustrating Evacuation test of reactor

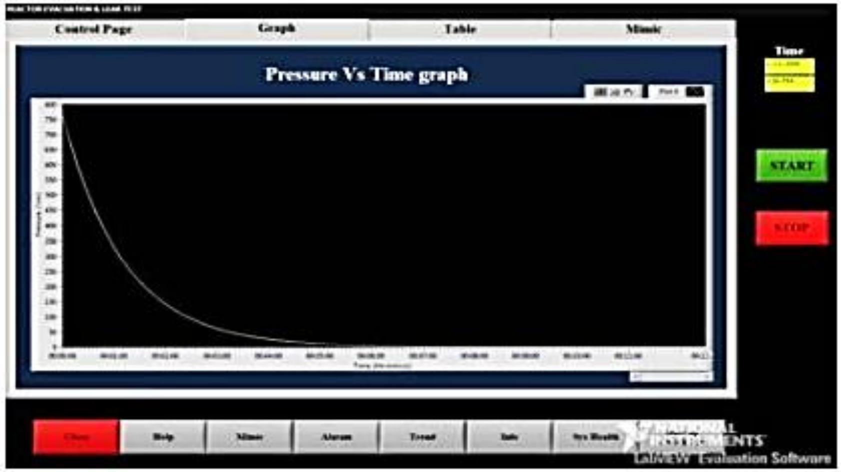


Fig. 4. Graph depicting Reactor Evacuation characteristics

Fig. 5. Screen shot illustrating completion status of the process

PROCESS AREA:
CVD REACTOR SYSTEM AUTOMATION:
CVD REACTOR SIMULATION RESULTS (PART 3 OF 7)

- TCS and H2 are flow controlled by flow transmitters according to their feed schedule to maintain the reactor pressure at 4-5 bars (72.5 psi)
- The outlet pressure valve is regulated accordingly to obtain characteristics shown in Fig. 6 and 7

Ref.: Design & Process Control of Siemens Polysilicon CVD Reactor: Kurnool, Andhra, Pradesh, 12Dec2015

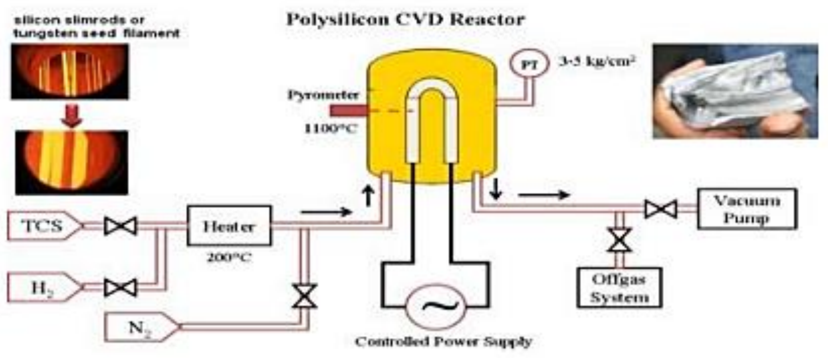


Fig. 1. Block diagram of poly -silicon CVD reactor [7], [8]

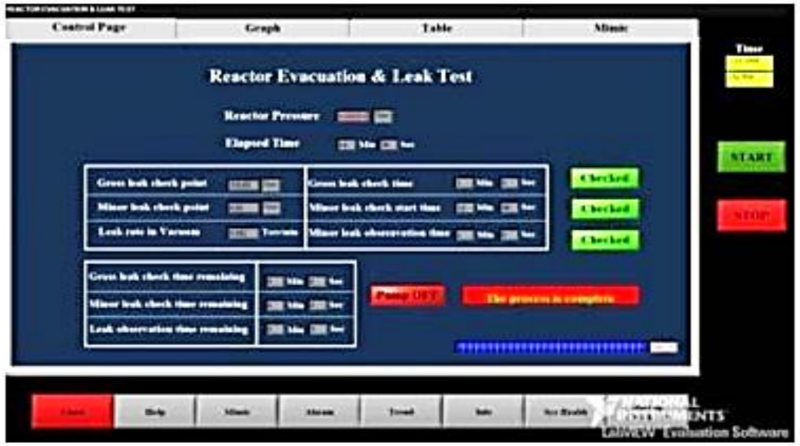


Fig. 6. Screen shot of mimic page for Feedrate scheduling

Fig. 7. Characteristics of TCS and Hydrogen feedrate as scheduled

PROCESS AREA:
CVD REACTOR SYSTEM AUTOMATION:
CVD REACTOR SIMULATION RESULTS (PART 4 OF 7)

- Reactor vessel with slim Tungsten rods are heated up to 1100.℃ with 230 VAC single phase power supply and the 5000 A current required for heating is controlled with a Thyristor control panel
- The structure with the reactor and filaments is modeled in Fig. 8
- The cylindrical vessel with length (l) and diameter (d) is considered with an inner radius of heater r1, outer radius of cylinder r2, and with an outer cover radius r3
- Depending on the chemical composition of the cylinder with Tungsten, N2 gas, Stainless Steel, and glass boundaries the Heat Flow will be in a radial direction and has its circuit model shown in Fig. 9
- The system has an electric heater of heat capacity Ch connected with thermal resistance rh to a furnace and to the surroundings with a thermal resistance ro and with a heat capacity Cr
- The filament kept at temperature Th transfers heat to the surrounding air inside the furnace at temperature Ti through the thermal resistance Rh
- The heat flow in a radial direction is exposed to two different temperatures Ti at 900.℃ and To at 1200.℃ making the model a linear time variant system
- Dynamics of the vessel at a specific time is modeled using state space realization following the conduction and convection properties and thermodynamic principles using the following equations after Fig. 9

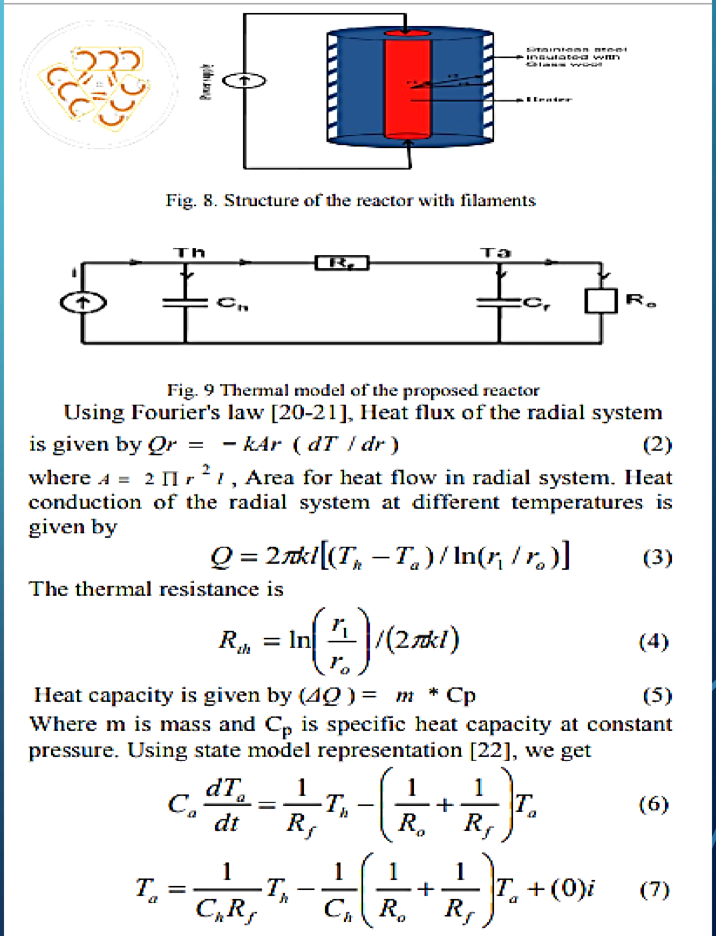


Fig. 8. Structure of the reactor with filaments

Fig. 9 Thermal model of the proposed reactor

Using Fourier's law [20-21], Heat flux of the radial system is given by $Qr = -kAr\ (dT\ /\ dr)$ (2)

where $A = 2\Pi r^2 l$, Area for heat flow in radial system. Heat conduction of the radial system at different temperatures is given by

$$Q = 2\pi kl[(T_h - T_a)/\ln(r_1/r_o)] \tag{3}$$

The thermal resistance is

$$R_{th} = \ln\left(\frac{r_1}{r_o}\right)/(2\pi kl) \tag{4}$$

Heat capacity is given by $(\Delta Q) = m * Cp$ (5)

Where m is mass and C_p is specific heat capacity at constant pressure. Using state model representation [22], we get

$$C_a\frac{dT_a}{dt} = \frac{1}{R_f}T_h - \left(\frac{1}{R_o} + \frac{1}{R_f}\right)T_a \tag{6}$$

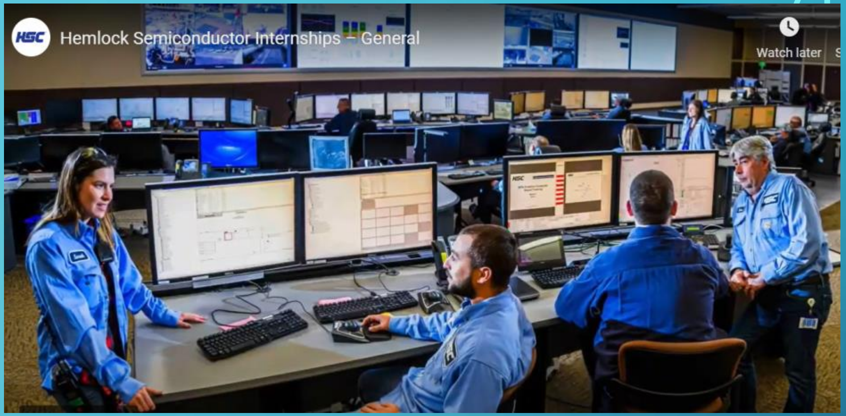
$$T_a = \frac{1}{C_h R_f}T_h - \frac{1}{C_h}\left(\frac{1}{R_o} + \frac{1}{R_f}\right)T_a + (0)i \tag{7}$$

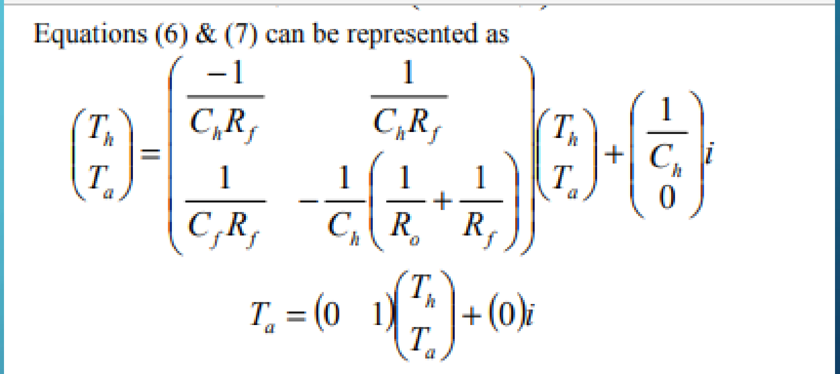
Ref.: Design & Process Control of Siemens Polysilicon CVD Reactor: Kurnool, Andhra, Pradesh, 12Dec2015

PROCESS AREA:
CVD REACTOR SYSTEM AUTOMATION:
CVD REACTOR SIMULATION RESULTS (PART 5 OF 7)

- A PID Controller in feedback control, controls the steady state and transient response as required
- This controller provides the most accurate and stable control, and is best used in systems which react quickly to changes with the energy added to the process
- Setting the controller parameters is achieved by tuning it using the Cohen-Coons method
- Tuned parameters using the Cohen-Coons method are:
  - t = 250
  - td = 15 sec
  - k = 1

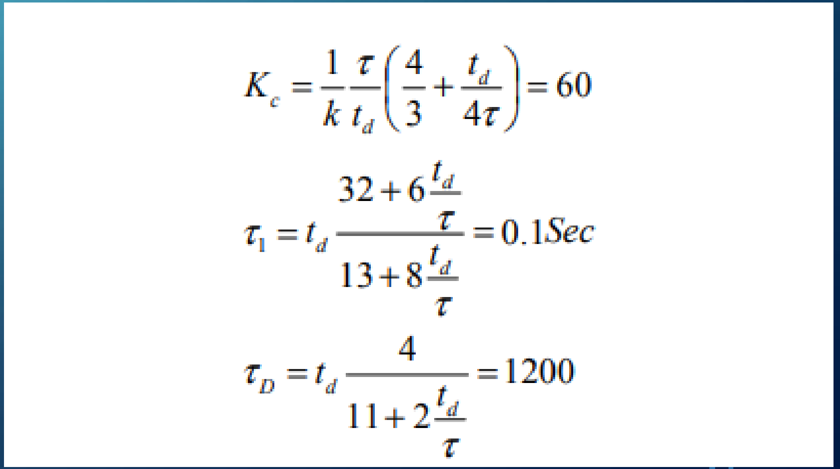
Ref.: Design & Process Control of Siemens Polysilicon CVD Reactor: Kurnool, Andhra, Pradesh, 12Dec2015




Equations (6) & (7) can be represented as

$$\begin{pmatrix} T_h \\ T_a \end{pmatrix} = \begin{pmatrix} \frac{-1}{C_h R_f} & \frac{1}{C_h R_f} \\ \frac{1}{C_f R_f} & -\frac{1}{C_h}\left(\frac{1}{R_o}+\frac{1}{R_f}\right) \end{pmatrix} \begin{pmatrix} T_h \\ T_a \end{pmatrix} + \begin{pmatrix} \frac{1}{C_h} \\ 0 \end{pmatrix} i$$

$$T_a = \begin{pmatrix} 0 & 1 \end{pmatrix} \begin{pmatrix} T_h \\ T_a \end{pmatrix} + (0) i$$


$$K_c = \frac{1}{k}\frac{\tau}{t_d}\left(\frac{4}{3}+\frac{t_d}{4\tau}\right) = 60$$

$$\tau_1 = t_d \frac{32+6\frac{t_d}{\tau}}{13+8\frac{t_d}{\tau}} = 0.1 Sec$$

$$\tau_D = t_d \frac{4}{11+2\frac{t_d}{\tau}} = 1200$$

PROCESS AREA:
CVD REACTOR SYSTEM AUTOMATION:
CVD REACTOR SIMULATION RESULTS (PART 6 OF 7)

- Process parameters are controlled and plant dynamics with steady state and frequency response are shown in screen shots Fig. 10, 11 and 12
- Practical and real-time values are obtained during the test is tabulated in Table II
- With the state model the system is completely observable, controllable and stable
- This SCADA system (hardware and software) globally monitors and ensures user friendly process control interface with real-time data trending along with data storage and retrieval, report generation and delivers progress visualization of each level in the process

Ref.: Design & Process Control of Siemens Polysilicon CVD Reactor: Kurnool, Andhra, Pradesh, 12Dec2015

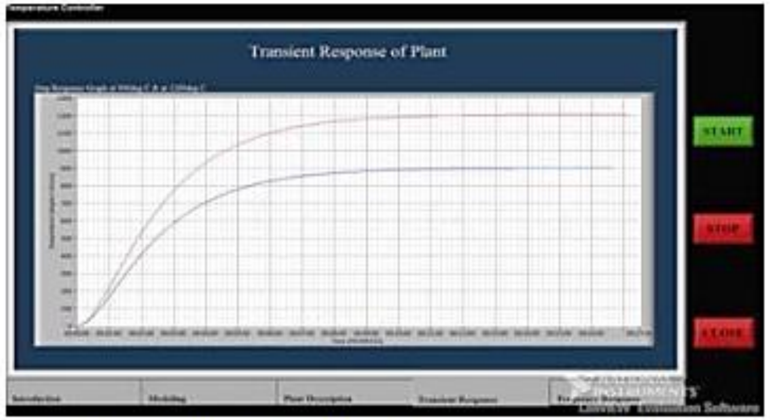


Fig. 10. Screen shot of transient response for temperature model

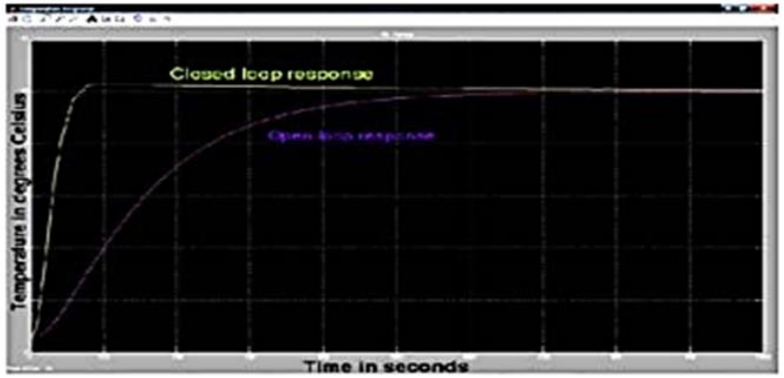


Fig. 11. Simulation of open & closed loop response of plant using MATLAB

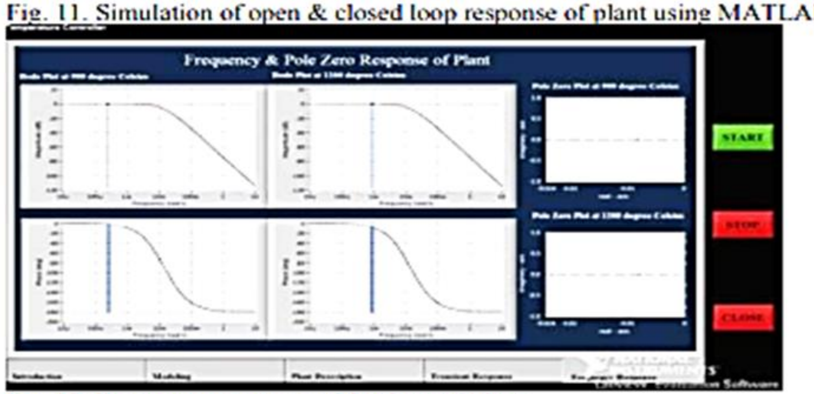


Fig. 12. Frequency response of the thermal plant

PROCESS AREA:
CVD REACTOR SYSTEM AUTOMATION:
CVD REACTOR SIMULATION RESULTS (PART 7 OF 7)

- The polysilicon ingot diameter measurement is monitored and captured by a camera vision based system
- The permissible growth of a polysilicon ingot is in the range of 100mm (4 in) to 150mm (6 in) diameter as illustrated in Fig. 13

Ref.: Design & Process Control of Siemens Polysilicon CVD Reactor: Kurnool, Andhra, Pradesh, 12Dec2015

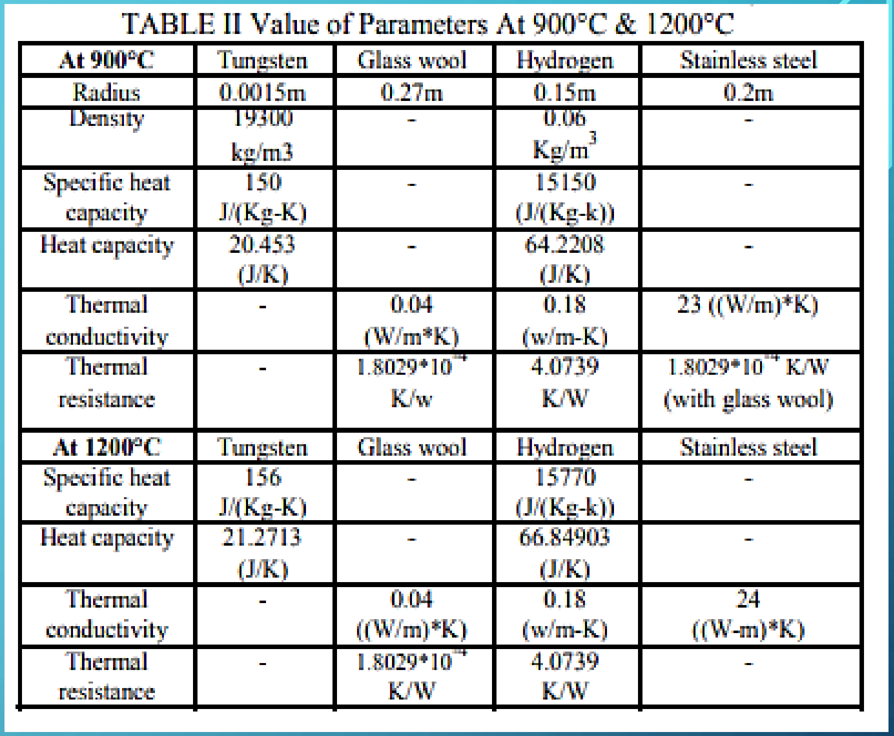


TABLE II Value of Parameters At 900°C & 1200°C

At 900°C	Tungsten	Glass wool	Hydrogen	Stainless steel
Radius	0.0015m	0.27m	0.15m	0.2m
Density	19300 kg/m3	-	0.06 Kg/m^3	-
Specific heat capacity	150 J/(Kg-K)	-	15150 (J/(Kg-k))	-
Heat capacity	20.453 (J/K)	-	64.2208 (J/K)	-
Thermal conductivity	-	0.04 (W/m*K)	0.18 (w/m-K)	23 ((W/m)*K)
Thermal resistance	-	$1.8029*10^{-4}$ K/w	4.0739 K/W	$1.8029*10^{-4}$ K/W (with glass wool)
At 1200°C	Tungsten	Glass wool	Hydrogen	Stainless steel
Specific heat capacity	156 J/(Kg-K)	-	15770 (J/(Kg-k))	-
Heat capacity	21.2713 (J/K)	-	66.84903 (J/K)	-
Thermal conductivity	-	0.04 ((W/m)*K)	0.18 (w/m-K)	24 ((W-m)*K)
Thermal resistance	-	$1.8029*10^{-4}$ K/W	4.0739 K/W	-

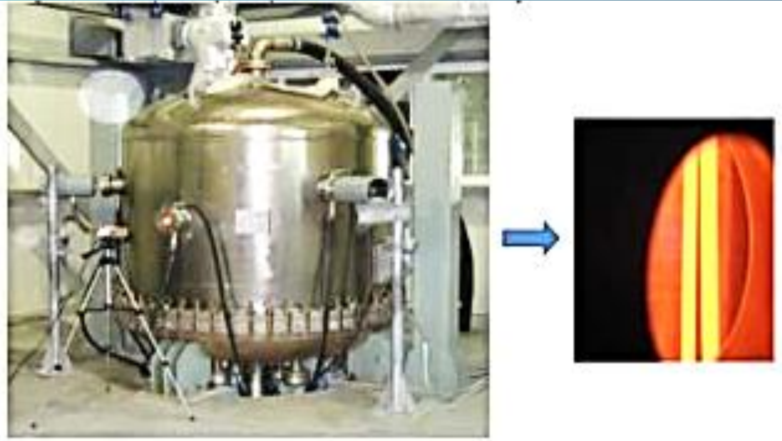
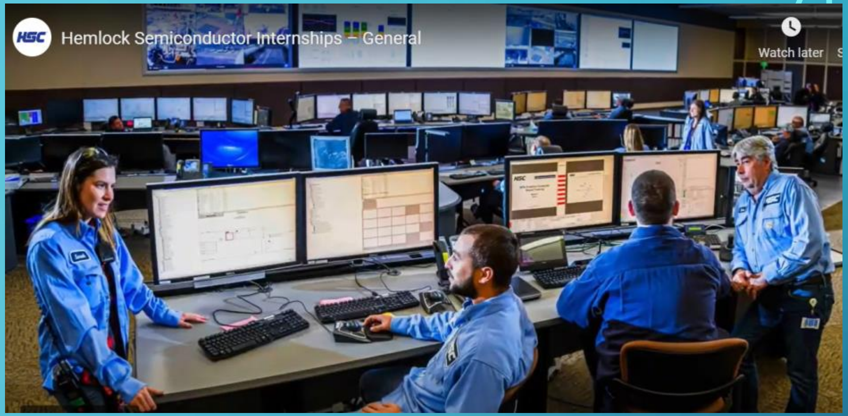


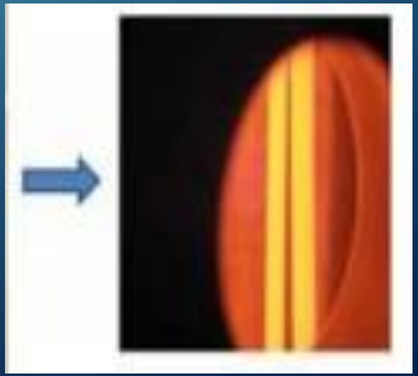
Fig. 13. Vision based Silicon Diameter Measurement

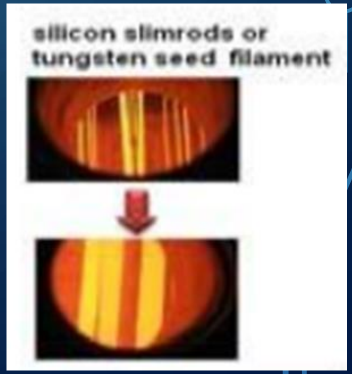
PROCESS AREA:
CVD REACTOR SYSTEM AUTOMATION:
CONCLUSIONS AND FUTURE WORK

- Optimized control of PVT parameters in a polysilicon CVD reactor was designed, modeled and developed to achieve productivity of polysilicon seed growth at high temperatures of 1050.℃ to 1100.℃ (2012°F)
- Process risk parameters of non-linear time variant CVD system are observable and controllable
- The system is highly stable at 900.℃ and at 1200.℃ (2192°F) the two worst temperatures cases for seed growth
- Specific heat capacities varies slightly from 150-156 J (Kg/K) across 900.℃ to 1200.℃ developing the PVT model at such high temperatures is very difficult
- Using NI LabVIEW software eased the construction of complex thermal structures and saved time acquiring the response of complex reactor modules
- The system is hazard and risk resistant with reproducible results capable of producing polysilicon ingots with a 10N purity level via a chemical route
- The GUI based HMI is reliable to the user with security and data management capacity and emergency handling capability of a process by making the system compliant with the required industrial standards ensuring safety

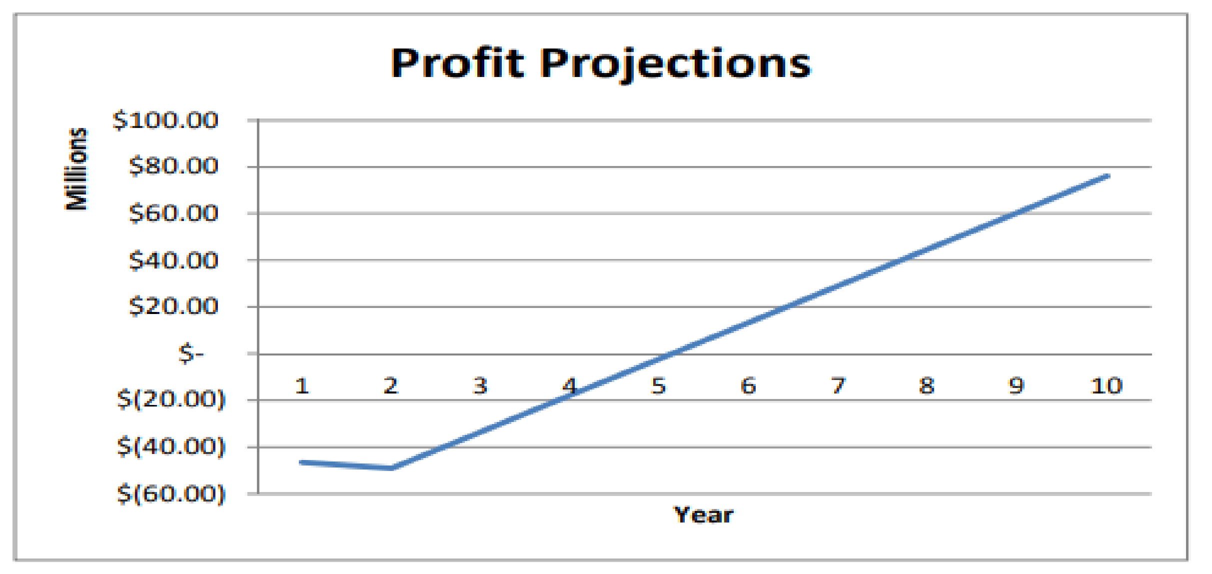
Ref.: Design & Process Control of Siemens Polysilicon CVD Reactor: Kurnool, Andhra, Pradesh, 12Dec2015







FINANCIALS, ADJUSTED FROM 2011 TO 2022 (AT 3% PER YEAR):



- This graph is the overall economic forecast for the facility PFD
- The first year is forecasted to be complete installation of the facility
- The second year is taken to be half capacity and only by third year is it in full capacity
- This yields an ROI of 66% allowing for additional consideration in safety of system performance as well as other miscellaneous costs not taken into account by an elementary financial analysis

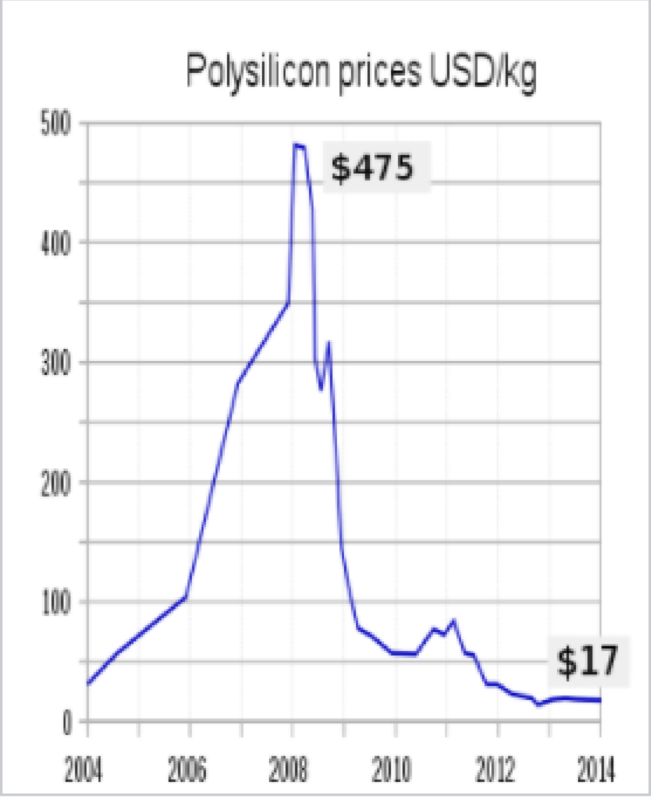
Ref. 1: Wikipedia Polycrystalline Silicon

Ref. 2: Production of Polysilicon using a Modified Siemens Process: Geng and Yu, 11May2011, ChemCAD 6.0.1

Financials	**Adjusted from 2011 Article: Production of Polysilcon using a Modified Siemens Process**		
Fixed Costs	Fixed costs of all process equipment calculated by ChemCad or industry standards		
ITEM No.	**Equipment Title** (ChemCad Calculation Tag)	**2011 Fixed Installed Cost** (USD)	**2022 Fixed Installed Cost** (USD)
1	Electric Arc Furnace, EAF	$550,000.00	$731,500.00
2	Fluidized Bed Reactor, FBR	$39,000.00	$51,870.00
3	FBR Separator # 1	$3,200.00	$4,256.00
4	Distillation Column # 1 (3)	$1,300,000.00	$1,729,000.00
5	Distillation Column # 2 (6)	$1,300,000.00	$1,729,000.00
6	Distillation Column # 3 (17)	$1,000,000.00	$1,330,000.00
7	Hydrolysis Reactor	$115,000.00	$152,950.00
8	Cyclone 1 (9)	$1,500.00	$1,995.00
9	Cyclone 2 (10)	$1,500.00	$1,995.00
10	FBR Separator # 2	$5,000.00	$6,650.00
11	Distillation Column # 4 (18)	$1,400,000.00	$1,862,000.00
12	Distillation Column # 5 (19)	$1,400,000.00	$1,862,000.00
13	CVD Reactor	$40,000,000.00	$53,200,000.00
	TOTAL BUDGET EST. (+ / 50%):	**$47,115,200.00**	**$62,663,216.00**
Variable Costs	Variable costs are calculated via the input and output of the system as well as tacking on additional overhead such as tax on revenue and a 325 day annual operation		
ITEM No.	**Subject**	**2011 Value**	**2022 Value (3% per year)**
1	Energy Cost	-$29,033,863.00	-$38,615,037.79
2	Silicon Cost	$46,526,789.84	$61,880,630.49
3	SiO2 Cost	$19,850,899.66	$26,401,696.55
Proposed Consumption			
1	H2	-$329,664.00	-$438,453.12
2	HCl	-$45,496.38	-$60,510.19
3	H2O	-$3,299.65	-$4,388.53
4	Mg Si	-$8,883,302.40	-$11,814,792.19
Operating Running BUDGET EST. (+ / 50%):		**$28,082,064.07**	**$37,349,145.22**
Reference:	Production of Polysilicon using a Modified Siemens Process, Geng & Yu, May 11, 2011		

WORLDWIDE POLYSILICON PRICE HISTORY IN USD/KG

- Polysilicon pricing has two possible areas
  - Contract Pricing, Long term price agreement
  - Spot Pricing, Current market value
- Higher purity can also change the present value of Poly-Si
- During slow times the Spot Price is lower than Contract Price
  - Due to lagging Solar PV installations worldwide
- During booming times a price rally occurs with Poly-Si
  - Spot prices will highly surpass Contract prices with high Solar PV
  - With demand greater than supply the Poly-Si cannot be acquired
  - Buyers will accept a large down payment with elevated long-term agreements to acquire large volumes of Poly-Si



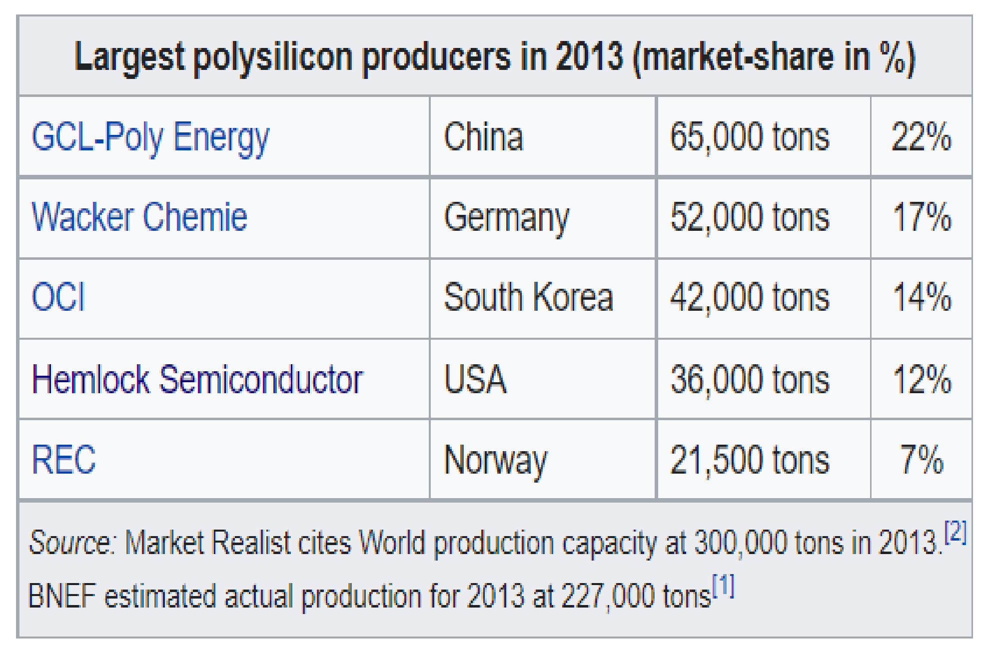
History of polysilicon spot prices

Ref.: Wikipedia Polycrystalline Silicon

WORLDWIDE POLYSILICON PRODUCTION MARKET %

- Hemlock Semiconductor Corporation is ranked # 4 worldwide (based on a 2013 Bloomberg New Energy Finance, BNEF estimate)
- Hemlock Semiconductor is ranked # 1 in U.S. as a Polysilicon manufacturer

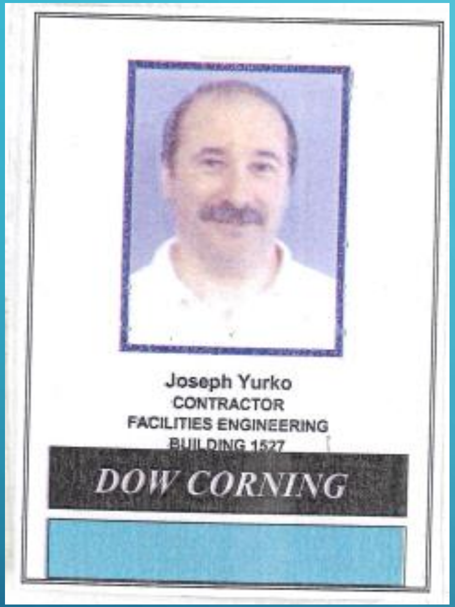
Ref.: Wikipedia Polycrystalline Silicon



Largest polysilicon producers in 2013 (market-share in %)			
GCL-Poly Energy	China	65,000 tons	22%
Wacker Chemie	Germany	52,000 tons	17%
OCI	South Korea	42,000 tons	14%
Hemlock Semiconductor	USA	36,000 tons	12%
REC	Norway	21,500 tons	7%

Source: Market Realist cites World production capacity at 300,000 tons in 2013.[2] BNEF estimated actual production for 2013 at 227,000 tons[1]

QUESTIONS? & ANSWERS!



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