Shell Building and Pattern Removal

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Shell Building

- Agenda
  - Objective of Shell Building
  - Basic Definitions
  - Binders
  - Refractories
  - Ceramic Shell Slurries
  - Shell Construction
  - Shell Drying
  - Shell Building Equipment
  - Slurry/Shell Characterization and Measurements

Shell Building Objective

- Produce a disposable ceramic vessel (shell mold) that will:
  - Replicate the visual and dimensional characteristics of the pattern
  - Withstand the forces and pressures associated with pattern removal process
  - Withstand the temperatures associated with preheat process
  - Withstand the temperatures, pressure and reaction from the molten metal associated with the casting process

Shell Building
Basic Definitions

- Binder – a mixture of a solvent (water or alcohol) and a solid (silica)
- Refractory – an inorganic, heat resistant ceramic material capable of enduring high temperatures
  - Refractory flour – a finely ground ceramic material mixed with the binder to form a slurry
  - Refractory grain (stucco) – a coarse refractory ceramic used to coat the pattern after a slurry dip
- Slurry – a mixture of a liquid binder and a refractory flour to form a “bath” used in the construction of a ceramic shell mold

Shell Building Binder

- A good binder must…
  - Provide a high temperature bond
  - Have low thermal expansion
  - Have stability that is manageable (ease of use)
  - Be economical

Shell Building Binder

- Three main types of binders used in investment casting
  - Colloidal silica
    - Water based
    - Most widely used in PIC industry
  - Ethyl silicate
    - Alcohol based
    - Nearly phased out due to EPA regulations and EH&S issues
  - Non-silica based binders
    - Mainly used for titanium and other reactive alloys

➢ We will focus on colloidal silica in this presentation

Shell Building
Binder - Colloidal Silica

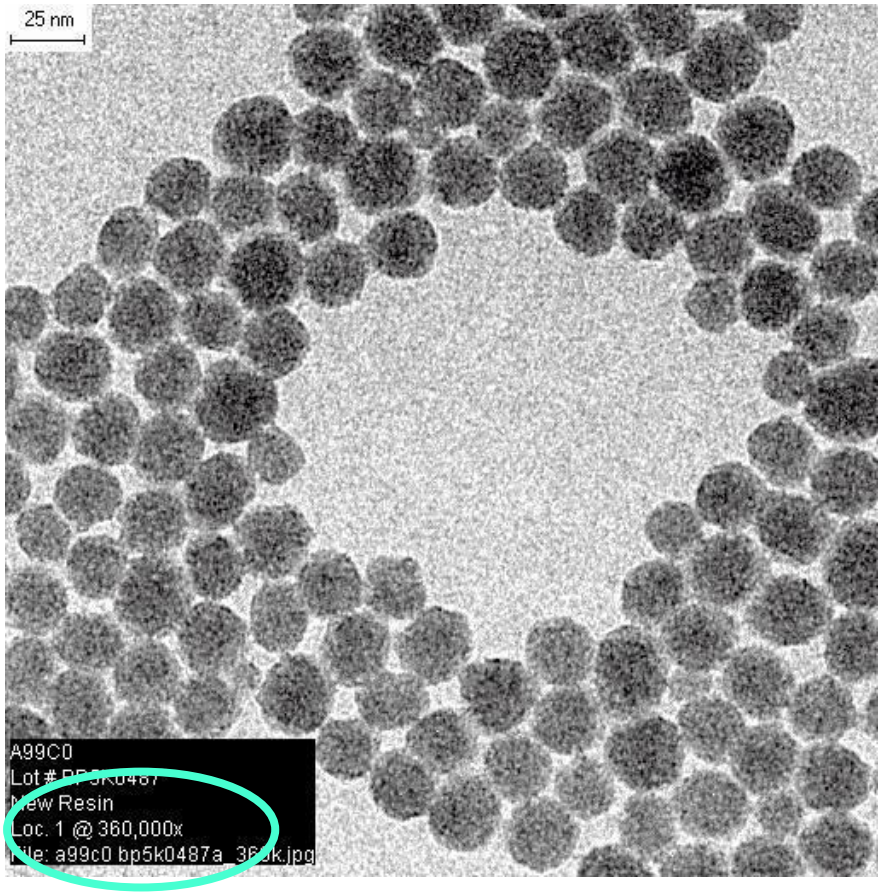
- What is colloidal silica?
- How does colloidal silica work?
- Why use colloidal silica?

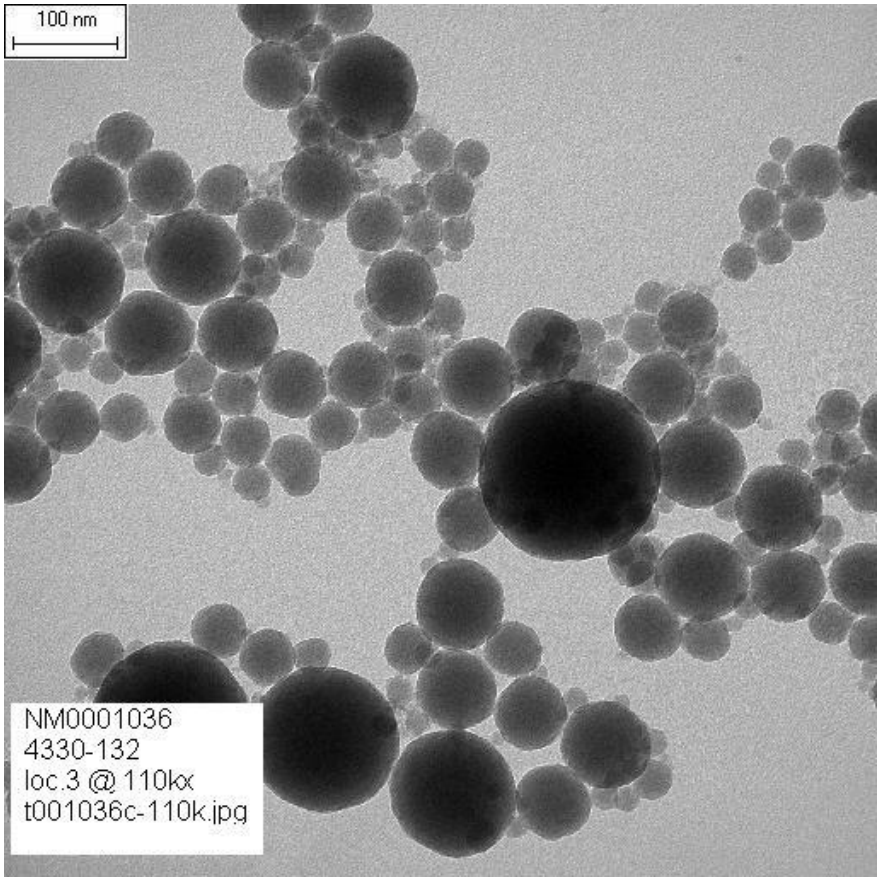
Shell Building
Binder - What is Colloidal Silica?

- Colloidal silica - refers to a stable dispersion of discrete amorphous particles of silicon dioxide (SiO_2).
  - Amorphous - non-crystalline – very resistant to thermal shock
  - Dispersion - a scattering of solids in a liquid
  - Also referred to as a “silica sol”

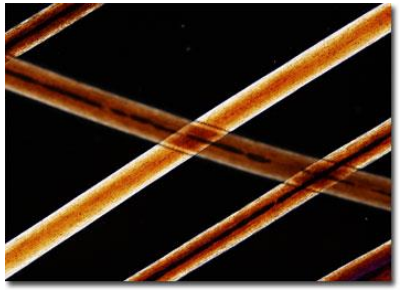
Colloidal silica products are clear to milky-white, depending on particle size

Shell Building
Binder - Colloidal Silica Particle



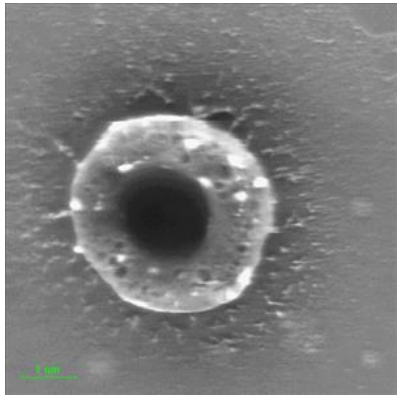


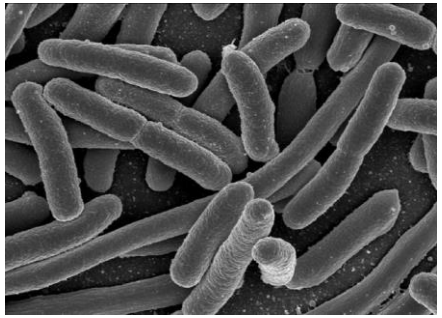
Fact: A Nanometer is One Billionth of a Meter… or 0.00000004 Inches!



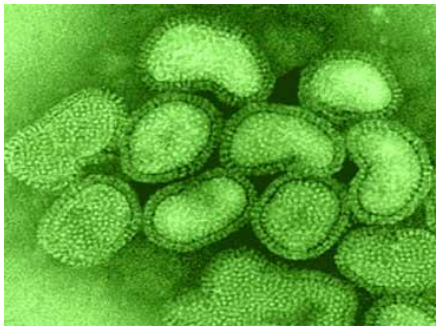
Human hair diameter: 100,000nm

Red blood cell diameter: 10,000nm



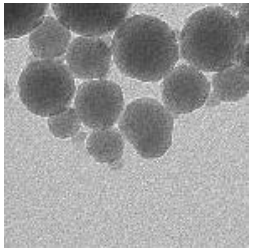


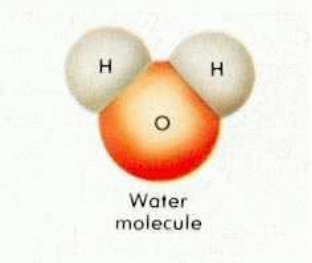
Typical bacteria: 2000 x 700nm



Flu virus: 100nm

Investment casting colloidal silica: 7-16nm



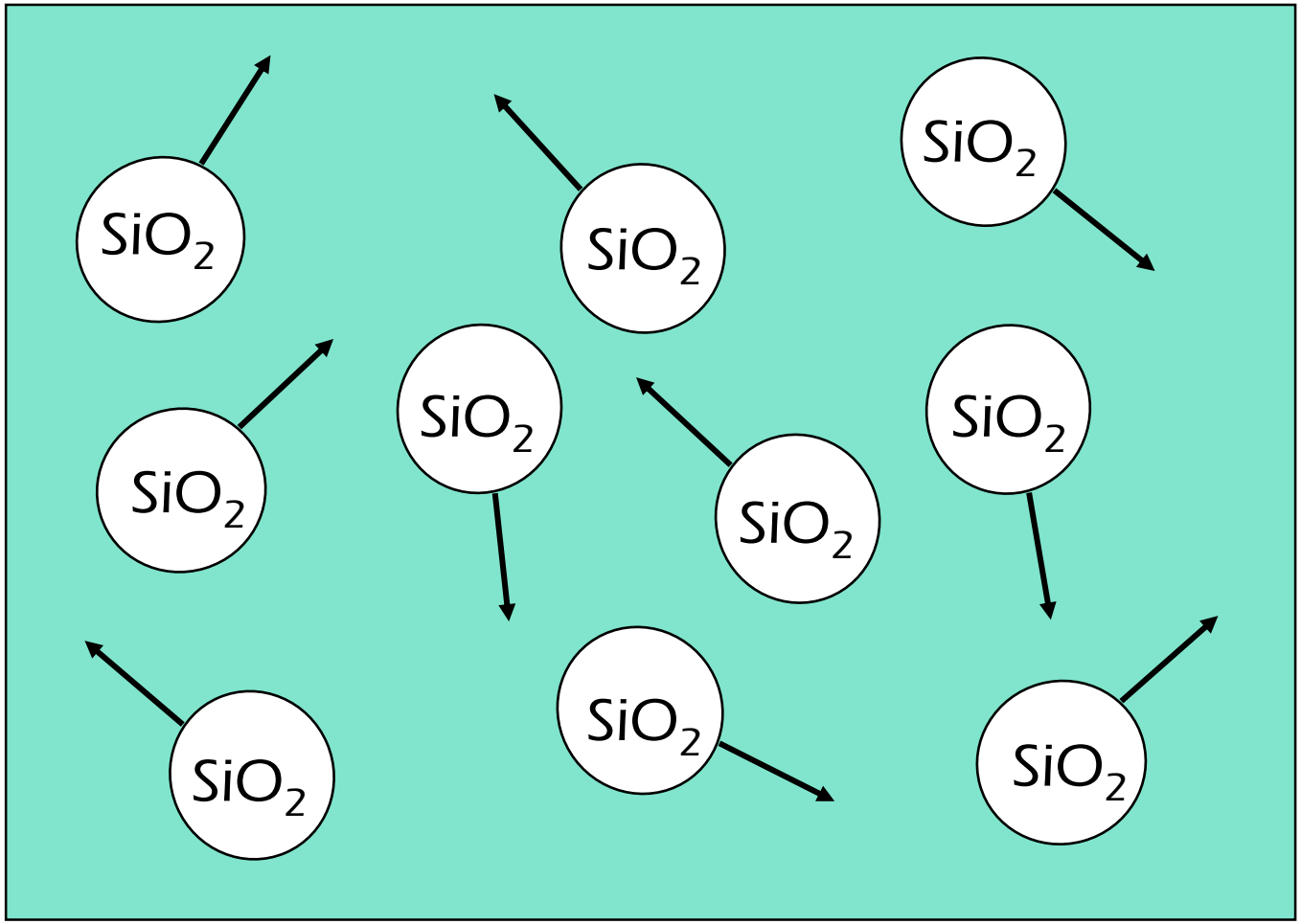


Water molecule: 0.278nm

A colloidal silica particle is only about 30x larger than a water molecule – not very big!

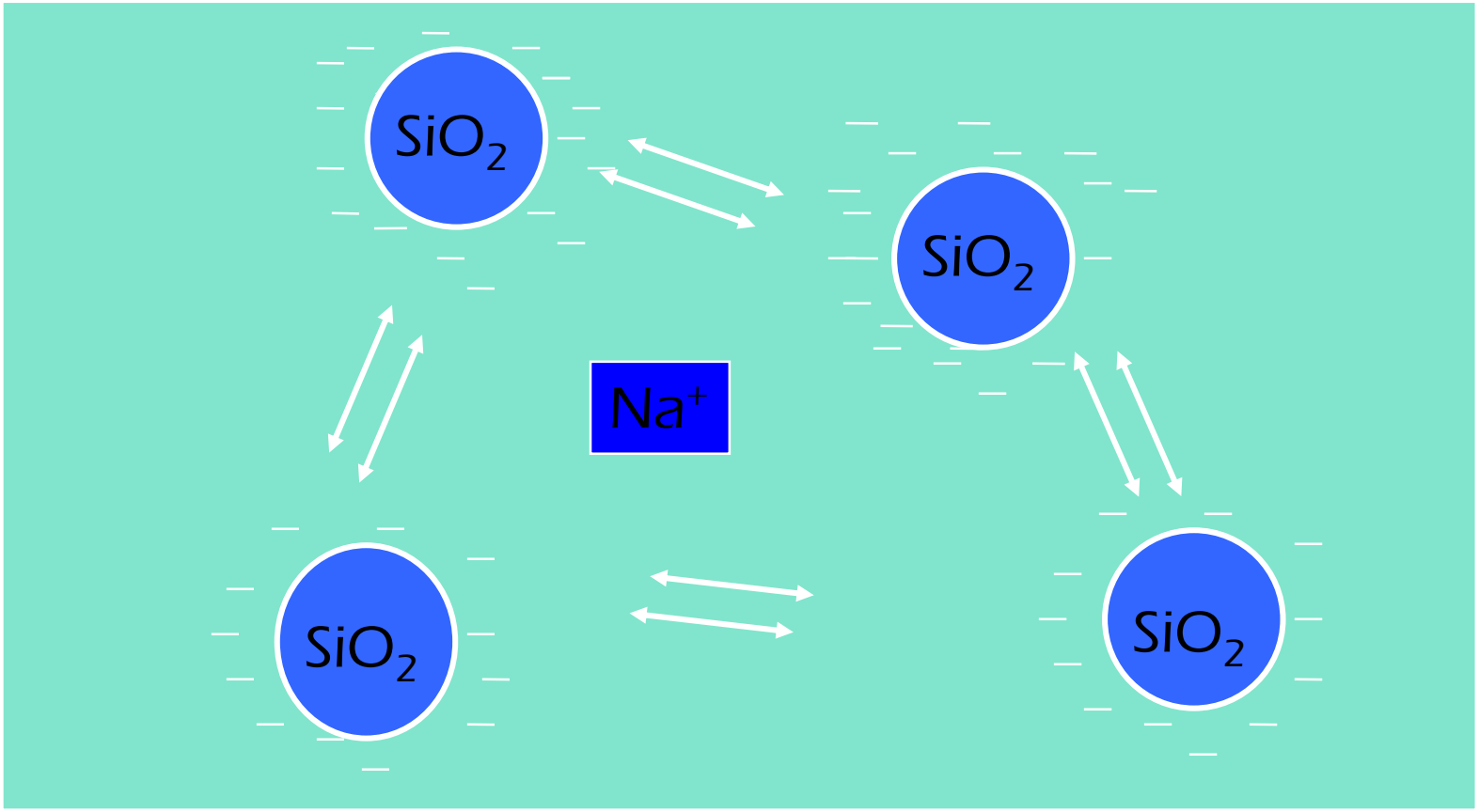
Shell Building
Binder - Why Don't the Particles Sink?

- Brownian Motion
  - Brownian forces overcome the force of gravity



Shell Building
Binder - Electrical Repulsion Stability

- **Stability created by electrostatically inhibiting collisions**

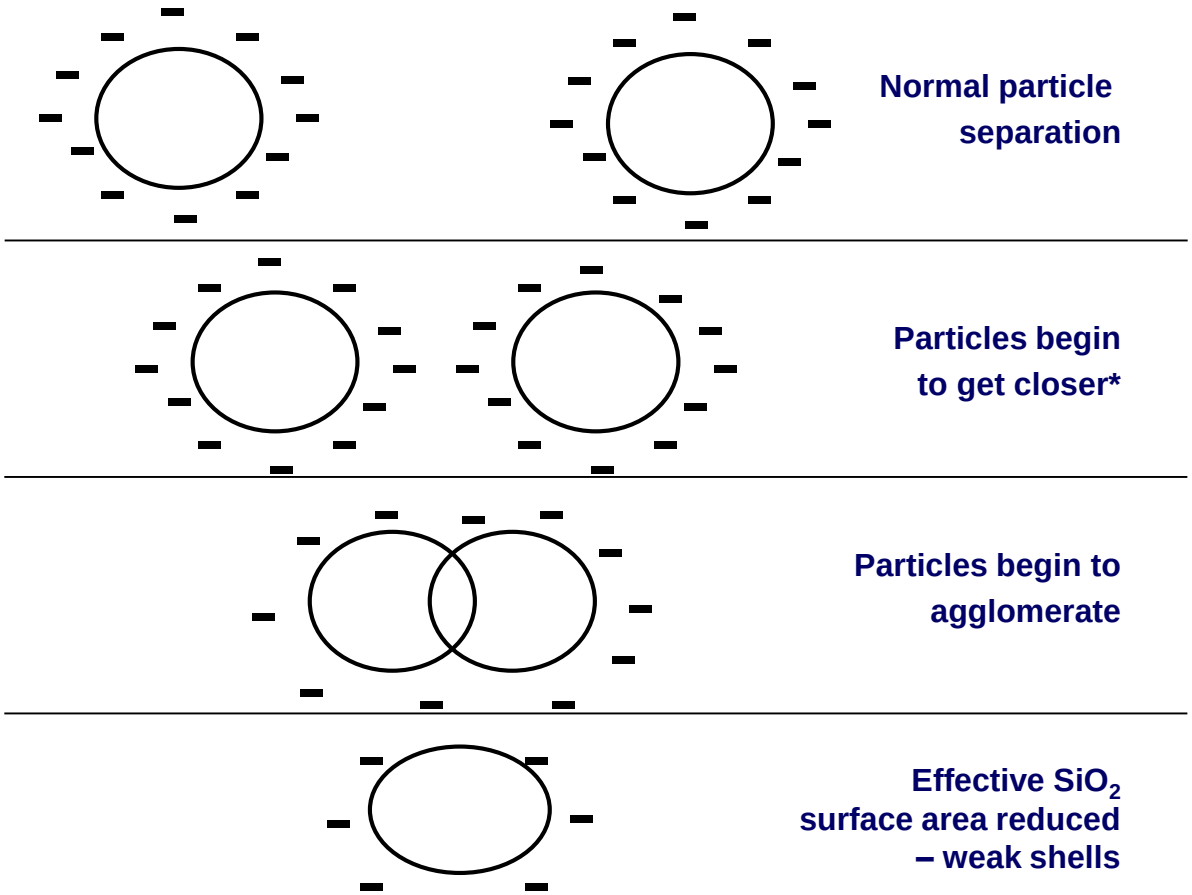


Shell Building
Binder - Colloidal Silica Instability

- Colloidal silica becomes unstable if:
  - Particle charge is altered or diminished
    - pH decrease
    - Conductivity increase
    - Salt (ions) contamination
  - Concentration of particles increases promoting particle collisions

☞ Both of these result in potential for agglomeration or gelation of the SiO_2 which causes irreversible damage to the binder

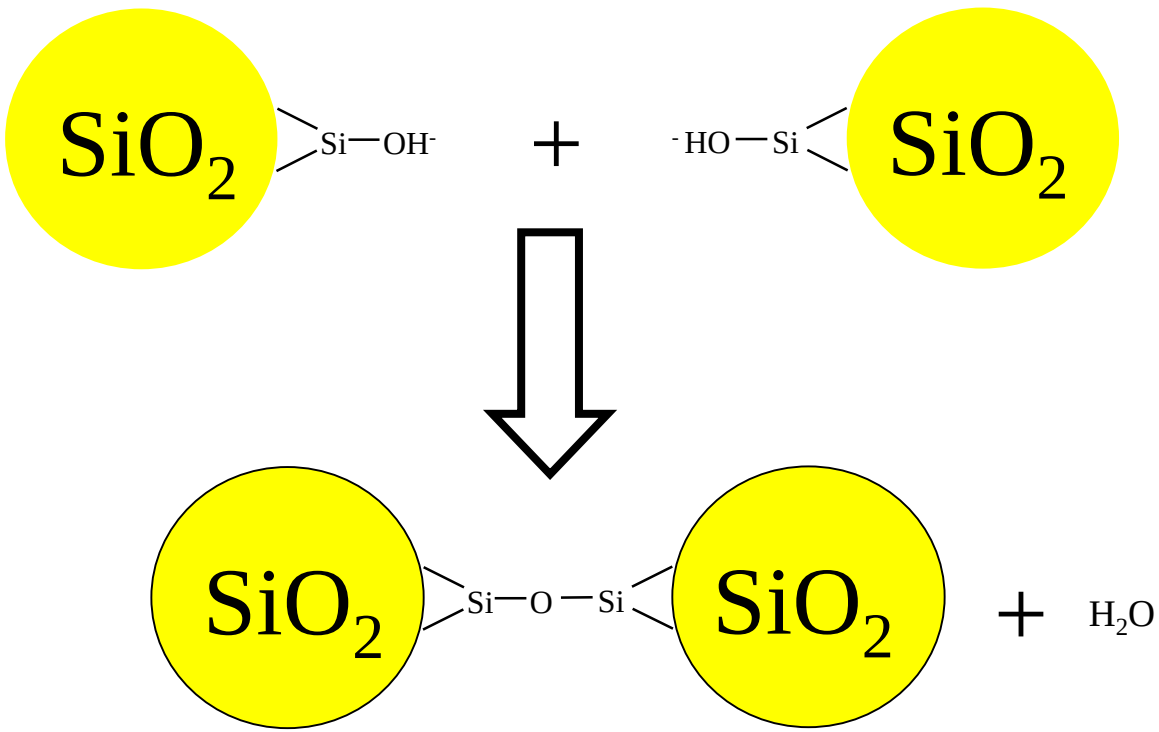
Shell Building
Binder - Colloidal Silica Instability



* Due to altering particle charge or increasing particle concentration

Shell Building
Binder - Colloidal Silica Reaction

- Colloidal silica particles are polymerized spheres of silicon dioxide
- The surface of these spheres consist of un-reacted silica in the form of silanol (SiOH-)
- When water is evaporating, the particles are forced together
- Upon contact they bond in the form of a gel
- This is a one way reaction – once it has gelled, it cannot be recovered
- We want this to occur on the shell, but not in the slurry!



Shell Building
So What Happens Next?

- Under green conditions (room temperature), a gel network is formed that holds the molds together
- Once the mold has been preheated, sintering forms a permanent ceramic bond that is much stronger

Shell Building
Binder - Colloidal Silica - Summary

- Positive aspects
  - Environmentally friendly - water is the solvent, no volatile organic compounds (VOC) concerns
  - Abundance - investment casting is a minor application of colloidal silica
  - Ease of use - straightforward application if controlled
  - Easy to control - simple tests required
  - Cost - relatively inexpensive

Shell Building
Binder - Colloidal Silica - Summary

- Negative aspects
  - Long final dry times - 24 to 48 hours to completely remove moisture
  - Presence of sodium can cause problems in some applications
    - Sodium is a flux for ceramics, in that it can make the ceramics turn soft at lower temperatures
    - This can result in deformed molds and deformed castings
  - Drying sensitive - colloidal silica shrinks as it dries
    - This shrinkage can cause stresses that might lead to surface defects in shell
  - pH sensitive

Shell Building
Binder - Other Liquid Components of a Slurry

- Polymer
- Water
- Wetting agent
- Antifoam
- Biocide

- Will be discussed more later

Refractories
Definition

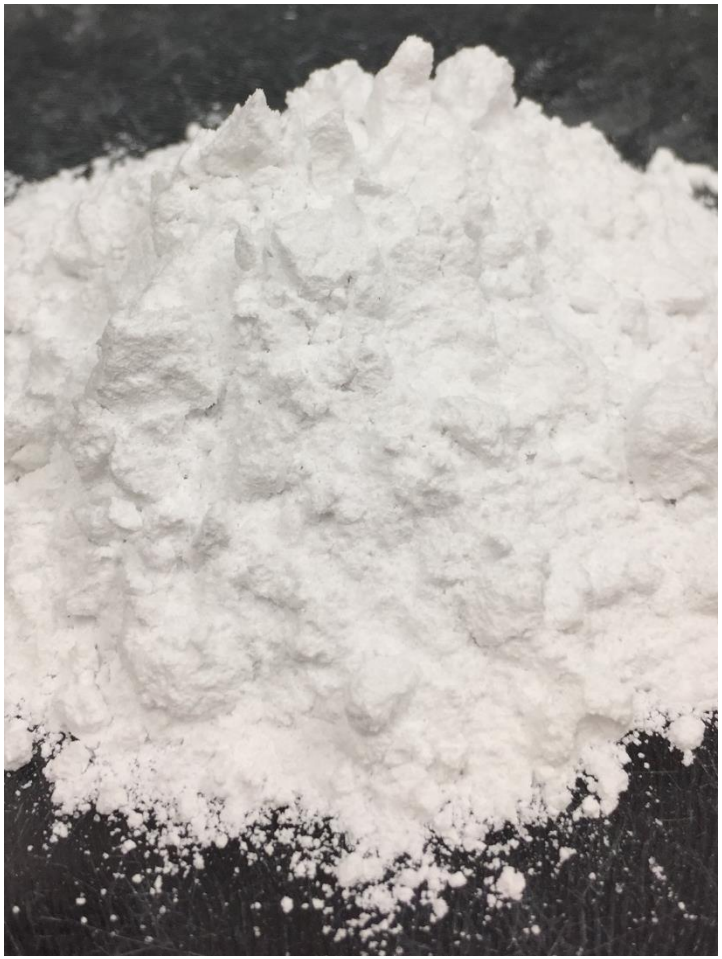
- Inorganic, non-metallic materials
  - Will withstand high temperatures
  - Such materials frequently are resistant to abrasion, corrosion, pressure and rapid changes in temperature
  - Note: for investment casting, we are most interested in temperature resistant properties

Shell Building
Refractory Properties

- Refractoriness
- Thermal expansion/thermal shock
- Thermal conductivity
- Density
- Leachability
- Reactivity - with alloy or binder
- Cost

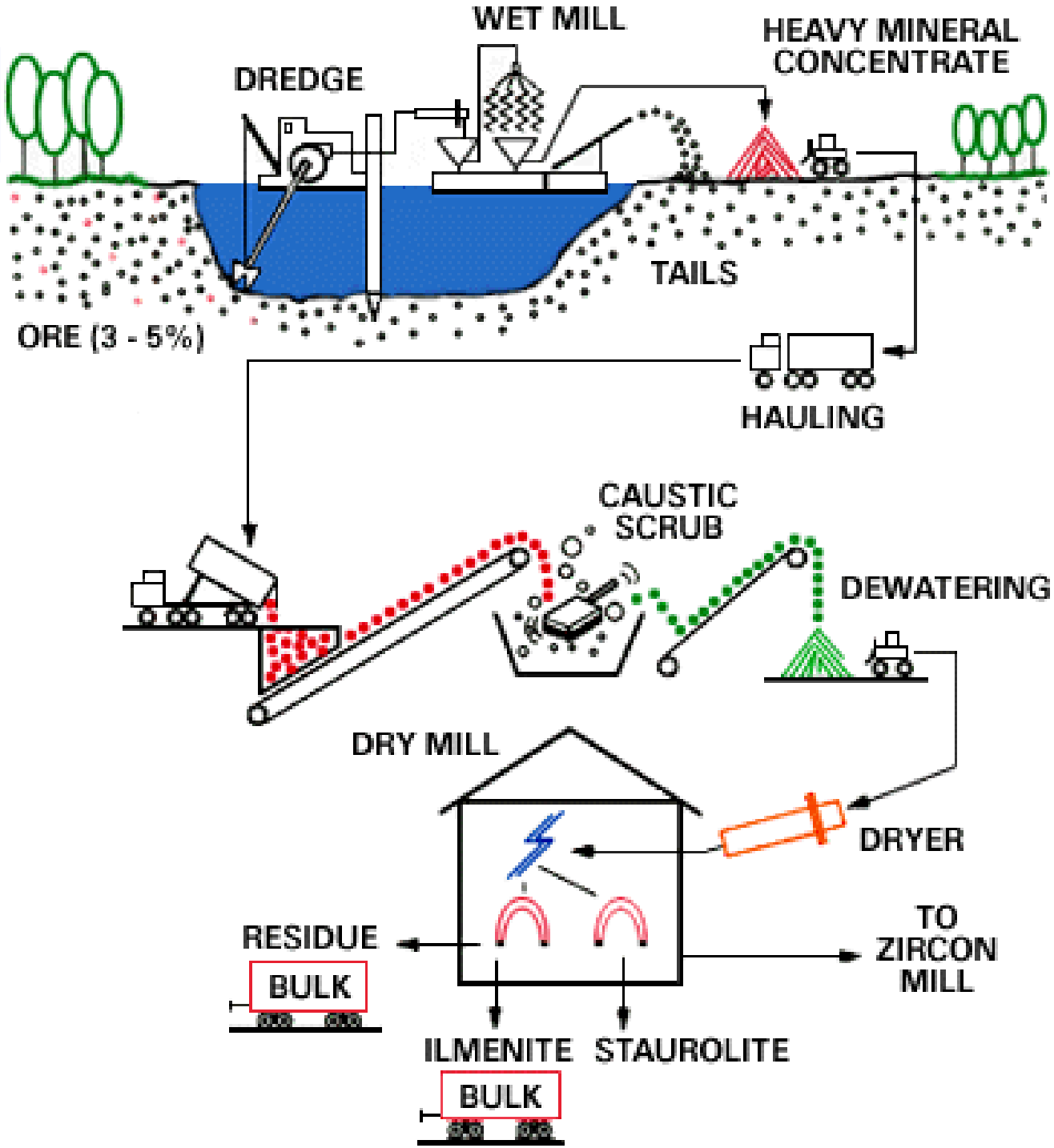
Shell Building
Refractories - Used in Investment Casting

- Zircon
  - Zirconium silicate
- Fused silica
- Aluminosilicates
  - Mulgrain
  - Molochite
  - Monofrax
  - Chamotte
  - Mullite
  - Clayrac
  - Euro-Sil
- Tabular alumina



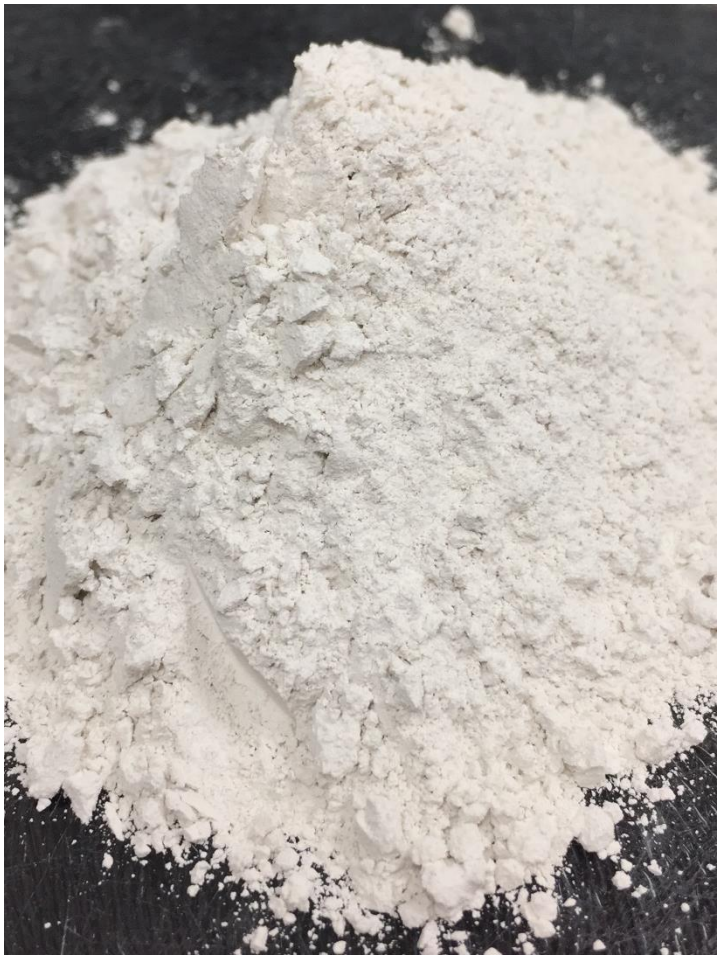
Shell Building Refractories - Zircon Source

- Byproduct of the TiO_2 mining process
- Naturally occurring element in nature
- Mined in a wet process
  - As heavy minerals are separated from other minerals through sedimentation and separation process
- Found in:
  - Georgia
  - Florida
  - South Africa
  - Australia


WET MILL
HEAVY MINERAL CONCENTRATE
DREDGE
TAILS
ORE (3 - 5%)
HAULING
CAUSTIC SCRUB
DEWATERING
DRY MILL
DRYER
RESIDUE
BULK
TO ZIRCON MILL
ILMENITE
STAUROLITE
BULK

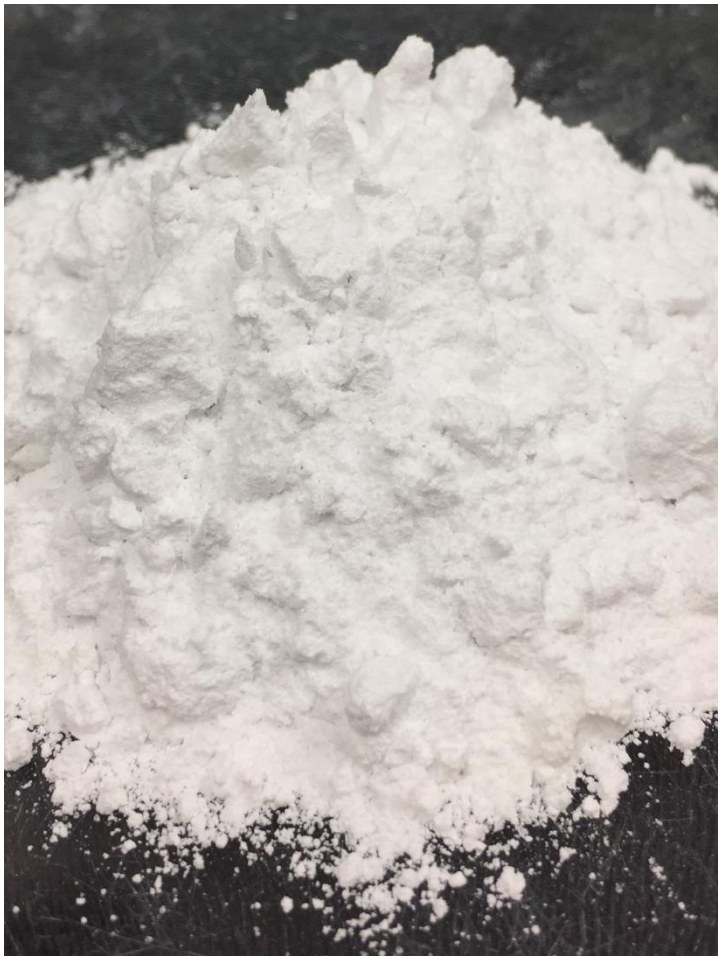
Shell Building
Refractories - Zircon Properties

- Chemistry
  - $ZrO_2 \bullet SiO_2$
- Molecular weight
  - 182.9
- Melting point
  - 2250°C (4082°F)
- Specific gravity
  - 4.54

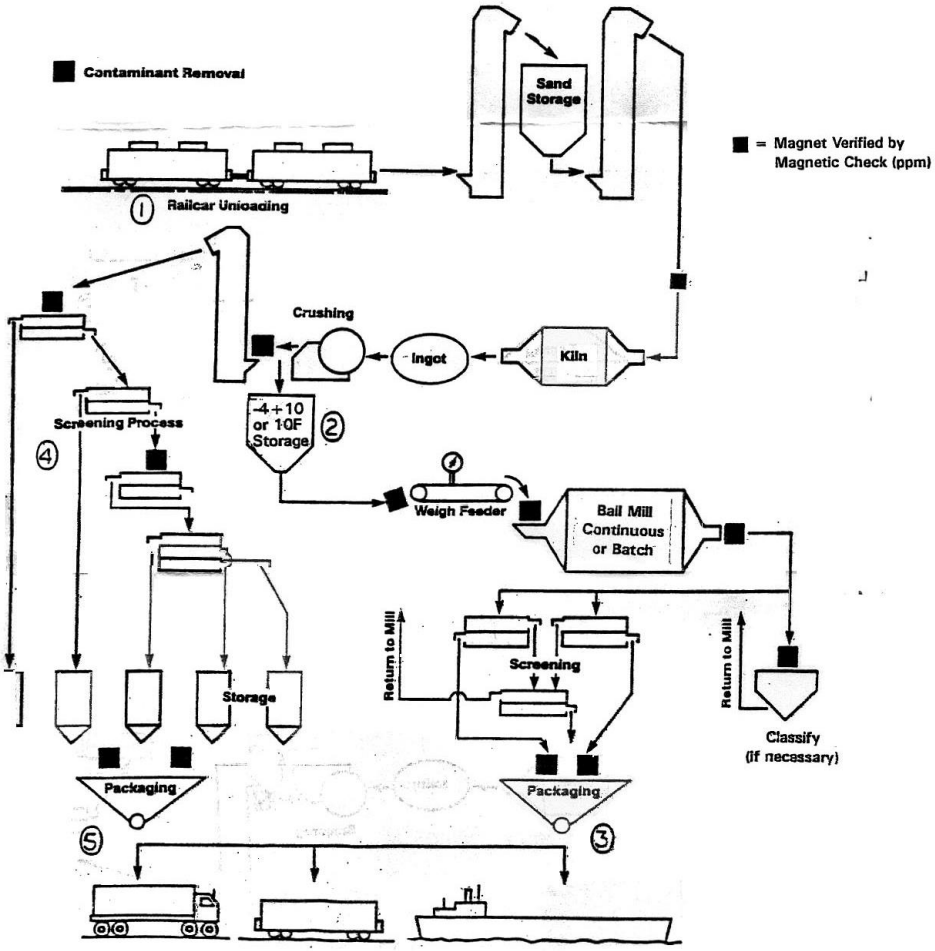


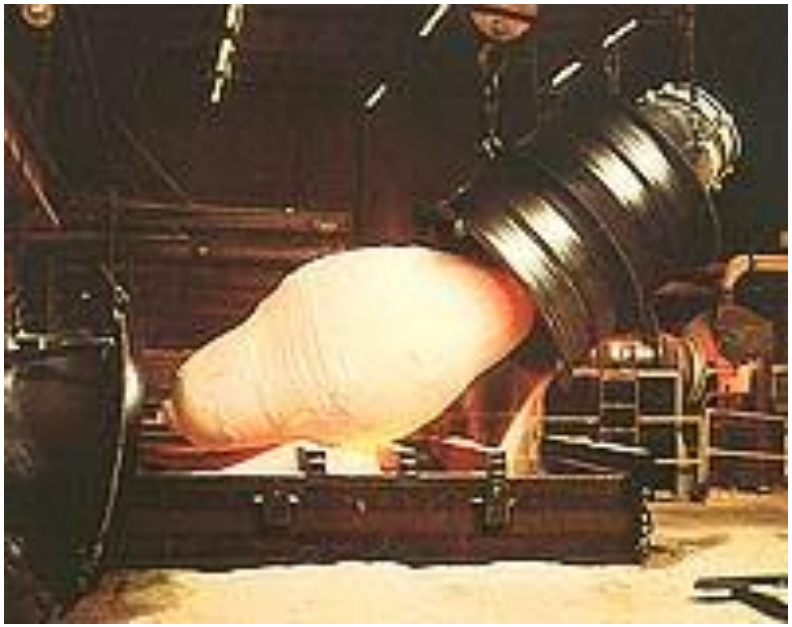
Shell Building
Refractories - Fused Silica Source

- Electrically fused high purity silica
  - Formed by melting crystalline silica into glass ingots
  - Ingots are crushed, screened and sized or ground



Shell Building
Refractories - Fused Silica Production



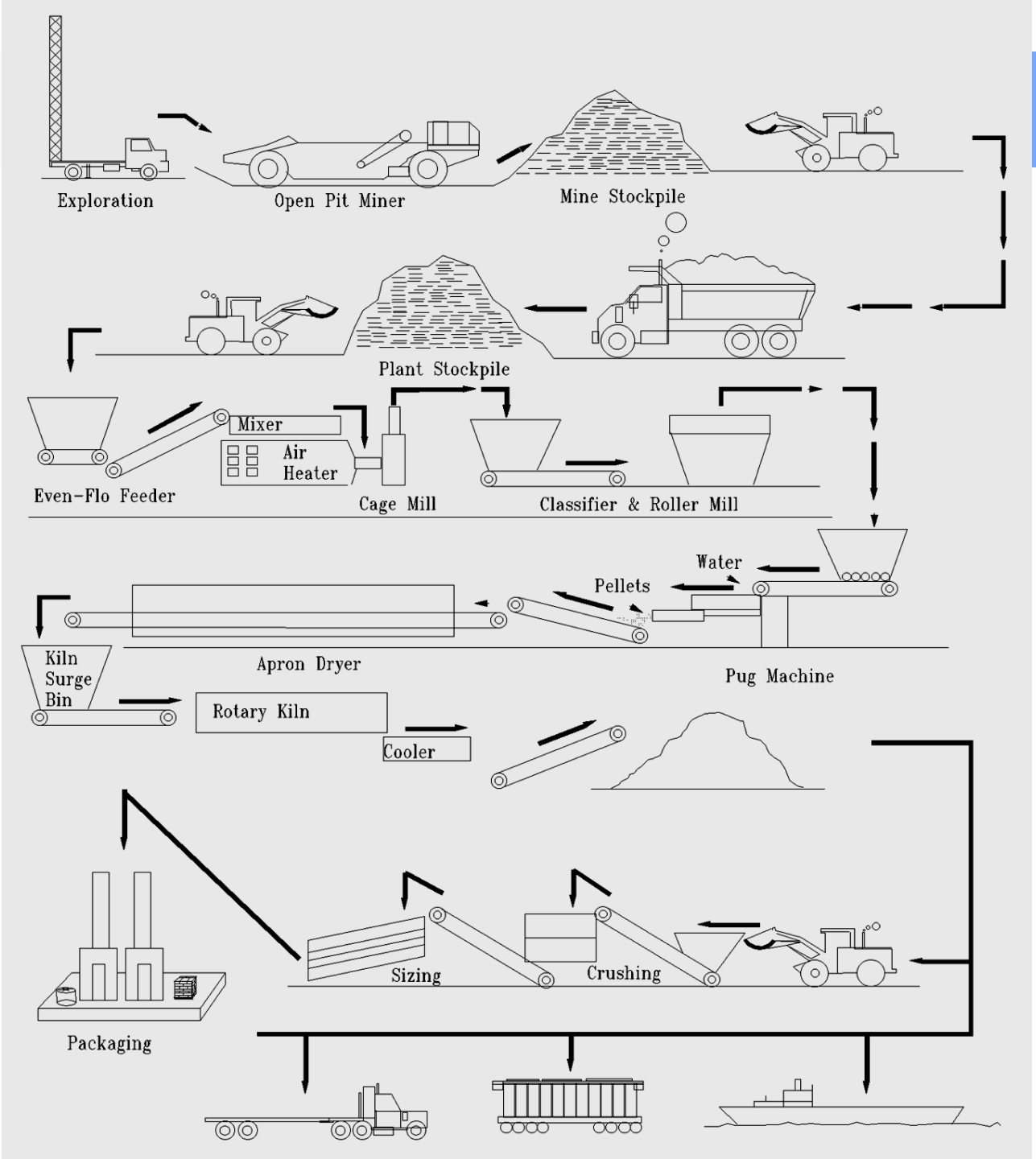


Shell Building
Refractories - Fused Silica Properties

- Extremely low coefficient of thermal expansion
- Consistent chemistry
- Transparent
  - Excellent heat transfer (radiant)
- Excellent high temperature strength and rigidity

Shell Building
Refractories - Aluminosilicates Source

- Refractory calcines made from high purity ore deposits
- Ore and clays typically combined to achieve desired chemistry
- Material calcined, crushed, screen and ground accordingly


Exploration
Open Pit Miner
Mine Stockpile
Plant Stockpile
Even-Flo Feeder
Mixer
Air
Heater
Cage Mill
Classifier & Roller Mill
Water
Pellets
Apron Dryer
Pug Machine
Kiln
Surge
Bin
Rotary Kiln
Cooler
Sizing
Crushing
Packaging

Shell Building
Refractories - Aluminosilicates Properties

- Various Al_2O_3 grades available
- High purity
- Iron, alkaline and alkaline earth percentages vary
- Relatively inexpensive compared to fused silica and zircon

Shell Building Refractories - Cost

Material	Flour cost $/ lb	Cost for Equivalent Volume
Fused silica	$ 0.50	$ 1.10
Zircon	$ 2.00	$ 9.20
Aluminosilicate: 60%	$ 0.30	$ 0.85
Aluminosilicate: 47%	$ 0.25	$ 0.66

Shell Building
Ceramic Shell Slurries

- Most foundries utilize at least two slurries
- Primary slurry
  - First one or two shell coats
  - Capture the detail of the pattern
  - Provide the surface to cast metal against
- Backup slurry
  - Used for all coats after the primaries
  - Build shell strength and bulk
  - Determines shell properties
  - Determines shell dimensions

Shell Building
Ceramic Shell Slurries - Primary Slurry

- Binder
  - Colloidal silica
  - Polymer - good adhesion properties - capture the detail
  - Surfactants
    - Wetting agent to wet out surface and detail
    - Antifoam to prevent air bubbles being trapped in detail
- Refractory
  - High percentages of zircon - ferrous based alloys
    - In slurry and stucco
    - Very good refractoriness
    - High density - flow properties
  - Zircon used at up to 100% in slurry or diluted (typically with fused silica)

Shell Building
Ceramic Shell Slurries - Backup Slurry

- Binder
  - Colloidal silica
  - Polymer
    - Good flexibility/ductility
    - Film former to reduce soak back
  - Surfactants (to lesser extent than primes)
    - Wetting agent to wet out shell
    - Anti foam to prevent air bubbles being trapped in detail
- Refractory
  - Fused silica and aluminosilicates almost exclusively
  - Fused silica – easier shell removal, “stiffer”, more expensive that aluminosilicates
  - Aluminosilicates – cheaper, can be more prone to hot deformation

Shell Building
Shell Construction

- A ceramic shell is made as follows:
  1. Clean the assembly of wax patterns in solvent to remove silicone, dirt, etc.
  2. Dip the assembly into the appropriate slurry (primary or backup) while rotating and manipulating to avoid air entrapment
  3. Remove from slurry and drain (time and manipulation) until thin and even coat remains
  4. Apply appropriate (primary or backup) stucco sand
  5. Allow pattern to dry
  6. Repeat steps 2-5 a number of times to achieve adequate shell thickness (note skip step 4 on final seal coat)

A typical ceramic shell is 1-2 primary coats, 4-6 backup coats and a seal coat

Shell Building
Shell Drying

- Objective
  - Utilize drying conditions to remove moisture as fast as possible without causing damage to the pattern/shell during drying
- Five factors dictate the drying time for every shell
  - Temperature – will impact drying, but not normally a factor that is changed due to adverse affect on wax pattern
  - Airflow – from fans or blowers
  - Humidity – lower RH promotes faster migration of moisture to surface of part
  - Part geometry – slots and holes slow down drying versus flat surfaces
  - Slurry system and shell construction sequence

Shell Building
Shell Drying

- Temperature
  - Maintain drying room at ±5°F
  - Allow waxes to stabilize at temperature prior to dipping
- Humidity
  - The lower the humidity, the faster the drying
  - Very expensive to lower humidity
- Airflow
  - Biggest bang for your buck!
  - Greatest influence on reducing drying times of shells
  - Provide from all directions

Shell Building
Shell Drying

HUMIDITY (%)	AIRFLOW (M/S)	BU COAT 1 Dry time (mins)	BU COAT 4 Dry time (mins)
40	0	210	590

Increasing airflow has a greater impact on dry time than lowering humidity

Shell Building
Shell Construction - Equipment - Slurry Tanks

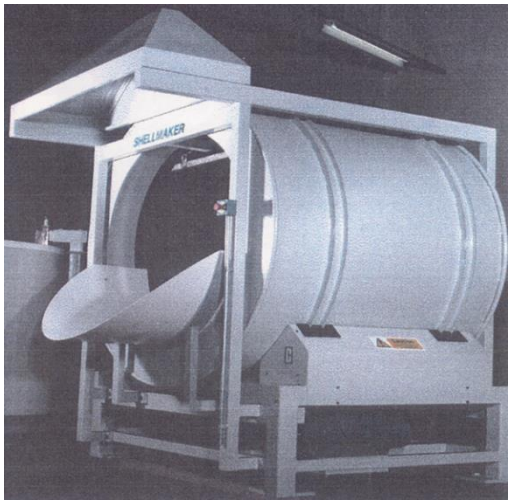
- Rotating tanks
  - Stationary plow
  - Tank rotates
  - Open surface – dipping area
  - Adequately keep slurry in suspension
  - Not good for “wetting out” a new slurry

Shell Building
Shell Construction - Equipment - Slurry Tanks

- Propeller tanks
  - Fixed or variable speed motor
  - One or two blades on shaft
  - “teardrop” tanks or cylindrical
  - Can generate heat in a slurry due to mixing friction
  - Can be used for “wetting out” a new slurry

Shell Building
Shell Construction - Equipment - Stuccoing

- Rainfall or Barrel Sander
  - Stucco cascades or "rains" onto wet pattern
  - Rainfall sander – bucket elevator used
  - Barrel sander – flights in barrel transfer stucco to top and it cascades down.



Shell Building
Shell Construction - Equipment - Stuccoing

- Fluid bed
  - Tank of stucco with a porous stone in bottom
  - Air is pumped through stone and “fluidizes” stucco
  - Wet patterns are easily dipped into stucco.

Shell Building
Shell Construction

- Shell construction techniques and equipment range from very basic to very complex.
  - Small or Art Casting operation
    - Dipping – manual or lift assist
    - Tanks – no mix or prop mix
    - Stucco application – rainfall/cat box or fluid bed
  - Hand dipping operation
    - Dipping – Manual – single trees
    - Tanks – propeller or rotating
    - Stucco Application – rainfall or fluid bed
  - Robot dipping operation
    - Dipping – Robot – multiple tree in a cluster
    - Tanks – propeller or rotating
    - Stucco Application – rainfall or fluid bed

Shell Building
Shell Construction Video - Art Casting

RANSOM & RANDOLPH

SuspendaSlurry® materials

Shell Building
Shell Construction Video - Aerospace

VA TECH

IC-AEROSPACE

Shell Building
Shell Construction Video - Commercial

VA TECH

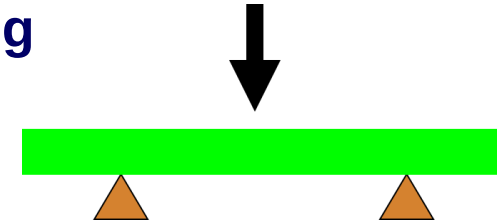
IC-COMMERCIAL

Shell Building
Slurry/Shell Characterization and Measurement

- Various properties of the ceramic slurry must be controlled through periodic measurement and adjustments
- These tests are know as slurry control tests
  - Simple tests onsite or by third party
  - Adjustments can be made with ingredients
- Standard slurry control tests
  - Viscosity - thinness or thickness of the slurry
  - Binder solids - the level of SiO_2 in the slurry
  - Refractory solids - the level of refractory in the slurry
  - Wetting ability
  - Antifoam ability
  - Binder pH
  - Bacteria levels

Shell Building
Slurry/Shell Characterization and Measurement

- The ceramic shell can be measured to determine/monitor shell properties
  - Modulus of Rupture (MOR)
    - The measure of the maximum stress at fracture when a sample is subject to three point bending



  - Adjusted Fracture Load (AFL)
    - The load bearing capacity
    - This is a function of the shell thickness and the MOR
  - Shell Permeability
    - Measures the ability/inability of air to pass through the shell
    - Trapped air/gas in the shell can lead to casting defects

Pattern Removal

Pattern Removal

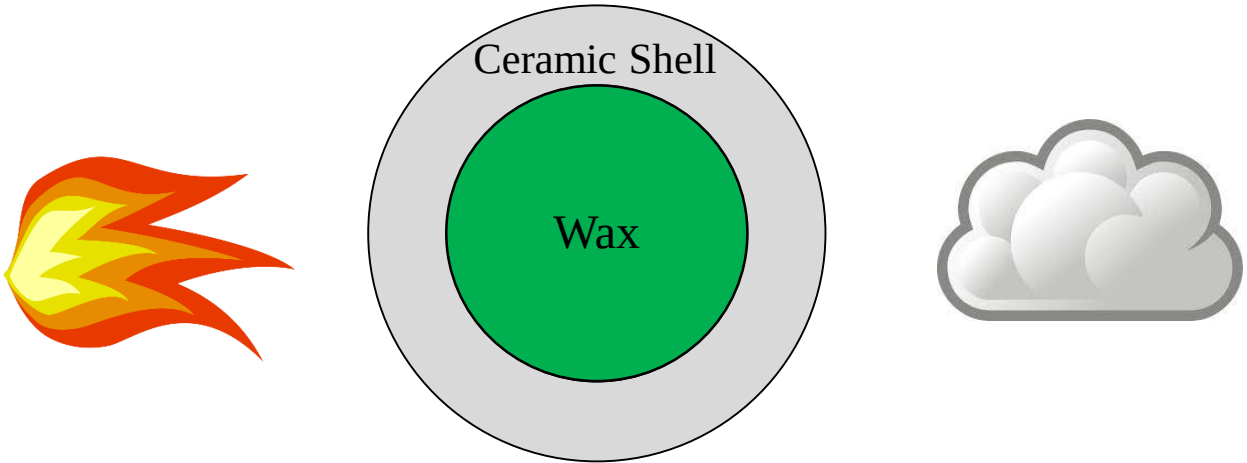
- Agenda
  - Basic definitions
  - Steam dewax
  - FlashFire dewax

Pattern Removal Definitions

- Dewax process - the process of removing the wax pattern from the ceramic shell by heat without damaging the ceramic shell
- Steam dewax - the dewax process is conducted in a pressure vessel where steam is the heat source
- FlashFire dewax - the dewax process is conducted in an oven and burners supply the heat source

Pattern Removal
Basic Process

- FlashFire dewax
  - Heat supplied by gas burner
  - Typically 1500°F
  - Heat transferred through shell to wax
  - Wax melts out
  - Wax is recovered
  - Residual wax/organics burned out
  - Equipped with afterburner
- Steam dewax
  - Heat supplied by steam (320°F)
  - Vessel is pressurized with steam
  - Steam condenses on surface of shell
  - Heat transferred through shell
  - Wax melts out
  - Wax is recovered
  - Residual wax/organics remain and require subsequent removal

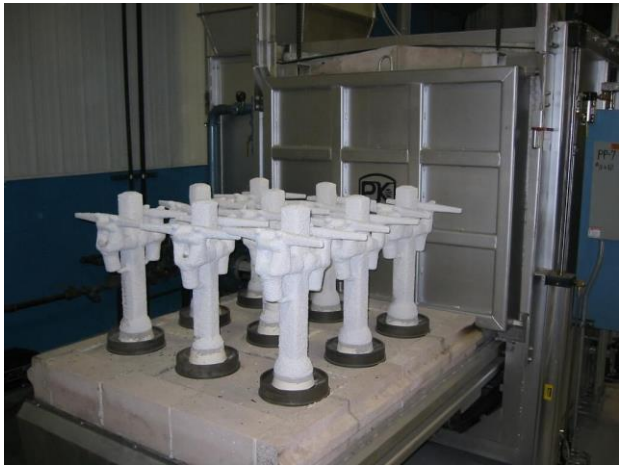


Pattern Removal
Steam Autoclave

Pattern Removal Boilerclave

https://youtu.be/pohbqid2fIE?t=28

Pattern Removal
FlashFire Dewax



Shell Building and Pattern Removal Summary

- Binders and Refractories are mixed together to form a slurry
- Slurries are specifically designed for application
- Shell molds are built layer by layer
  - Dip into slurry
  - Stucco with refractory grain
  - Dry
- A completed shell mold has the wax removed by steam or FlashFire dewax process
- Molds are now a “green” ceramic whose cavity has duplicated the detail, dimensions and geometry of the wax patterns
- Mold now proceed to Preheat and Casting operations

Acknowledgements

- Materials and information from the following companies were used in this presentation
  - Ransom & Randolph
  - Nalco Water - An Ecolab Company
  - Buntrock Industries
  - The Investment Casting Institute
  - LBBC Technologies
  - Pacific Kiln
  - Shell-O-Matic
  - VA Technology Ltd.

Questions

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