Separation Technologies LLC
A Titan America Business

Concentration of lunar ice from lunar regolith with Separation Technologies belt separator at cryogenic temperatures

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TITAN

Separation Technologies LLC

- **Potential Opportunities in Space**
- **Discovery Water at lunar pole**
  - **Electrostatic Belt Technology**
  - **20 years ago Ice-basalt separation**
- **ST belt separator now fully commercial**
  - **~ Million tons per year**
  - **~9 million tons total**
- **Enabling technology for lunar ice**

Separation Technologies LLC

- Focus of talk
- Electrostatic Belt Technology:
  Mature Technology Mineral Separation
- Estimate @ 1% ice → 50 kg/hr recovery
  @ 5k kg/hr on 50 kg separator @ 5 kW
- *While maintaining cryogenic*
  - No need to heat, recover gases
  - Or toxics, Hg, Pb, PH3?, HCl?, HF?

Separation Technologies LLC

- ***Who are we? What do we do?***
- ***History of ST***
- ***Conventional Electrostatic Separation***
- ***ST Electrostatic Belt Separator***
  - ***Myriad advantages***
- ***ST Experience with Industrial Minerals***
- ***Discussion of potential opportunities***

TITAN

- Building materials company founded in Greece in 1902
- More than €1 billion sales in 2010
- 13 cement plants in Europe, Eastern Mediterranean and U.S.
- Ready-mix concrete, blocks, aggregate and fly ash
- Vertically Integrated, Own and operate
- Continuous improvement
- Improvement one site → Improvement all sites

Process Cycle: R&D, Design, Build, Install, Own, Operate, Field Feedback ↺

TITAN Group

Separation Technologies LLC

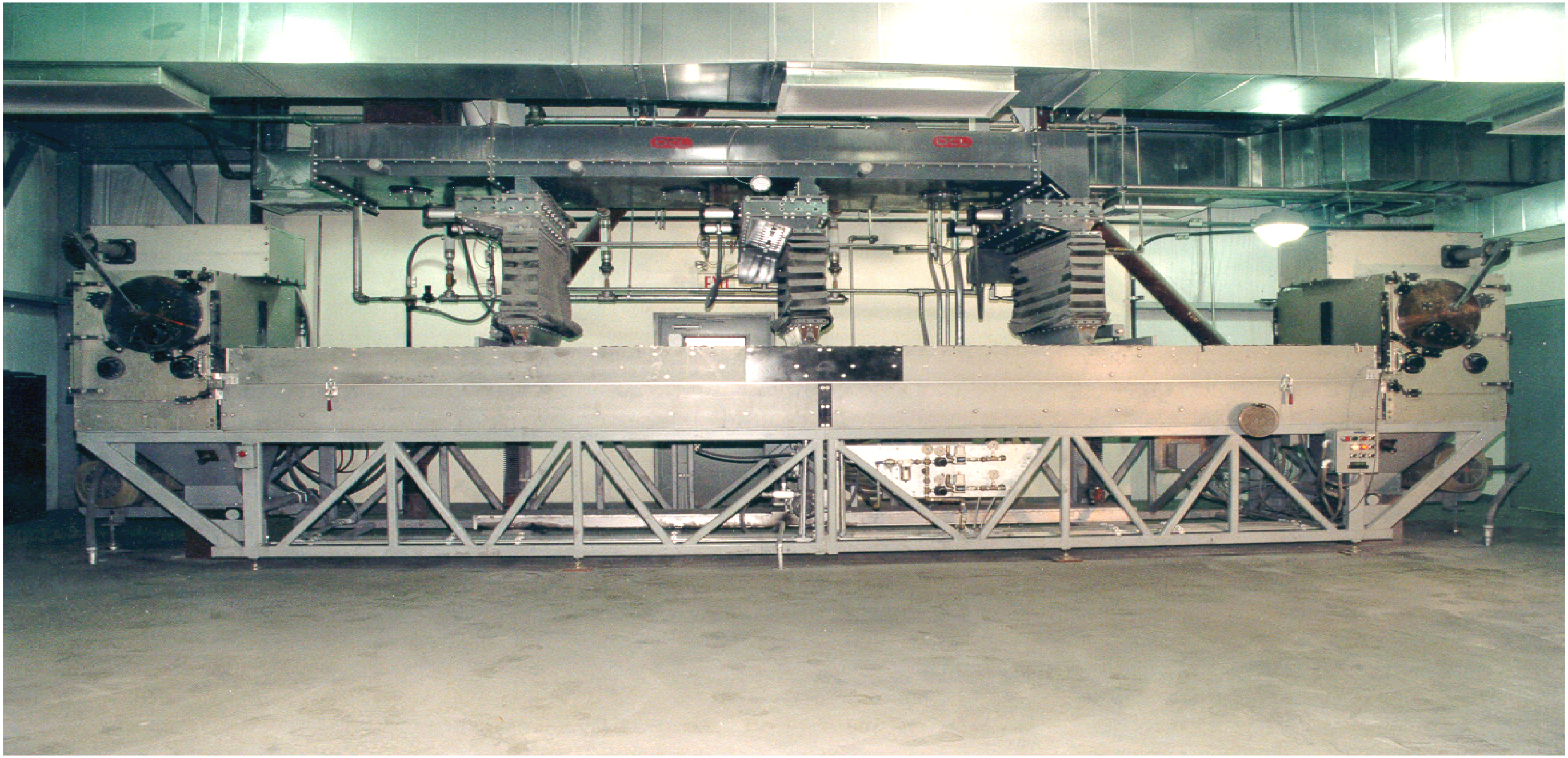
- ***What we do --***
  - Separate unburned carbon from fly ash with proprietary
    Electrostatic Belt Separator
  - **Sell clean high quality ProAsh® product to concrete producers as a cement substitute**
  - **Recycle high carbon product to the boiler to recover fuel value**
  - **Benefits of Fly Ash in Concrete**
    - **more durable and more workable concrete and structures**
    - **reduced landfill of power plant waste**
    - **fuel savings**
    - **reduced greenhouse gas (CO2) emissions**
- **Market Issues:**
  - **Cement: Bulk Commodity Material: sold on quality & price**
  - **Fly Ash is cheaper substitute; even more so**
  - **Titan & ST approach → Efficient & Highly Reliable Equipment**

History of Separation Technologies

- 1989 - Founded by M.I.T. engineer* to develop ***Electrostatic Belt Separator***
- 1995 - Begins commercial fly ash processing
- 1997 - Partners with Titan America at Progress Energy NC
- 2002 - Titan America acquires ST
- 2002 - First international project in Scotland
- 2004 - Teams with Lafarge to develop UK market
  - 4 UK installations by 2008
- 2010 – Lafarge Poland installs ST technology
- Currently – ST Installations at 12 Power Plants
  - 18 separators 4 countries

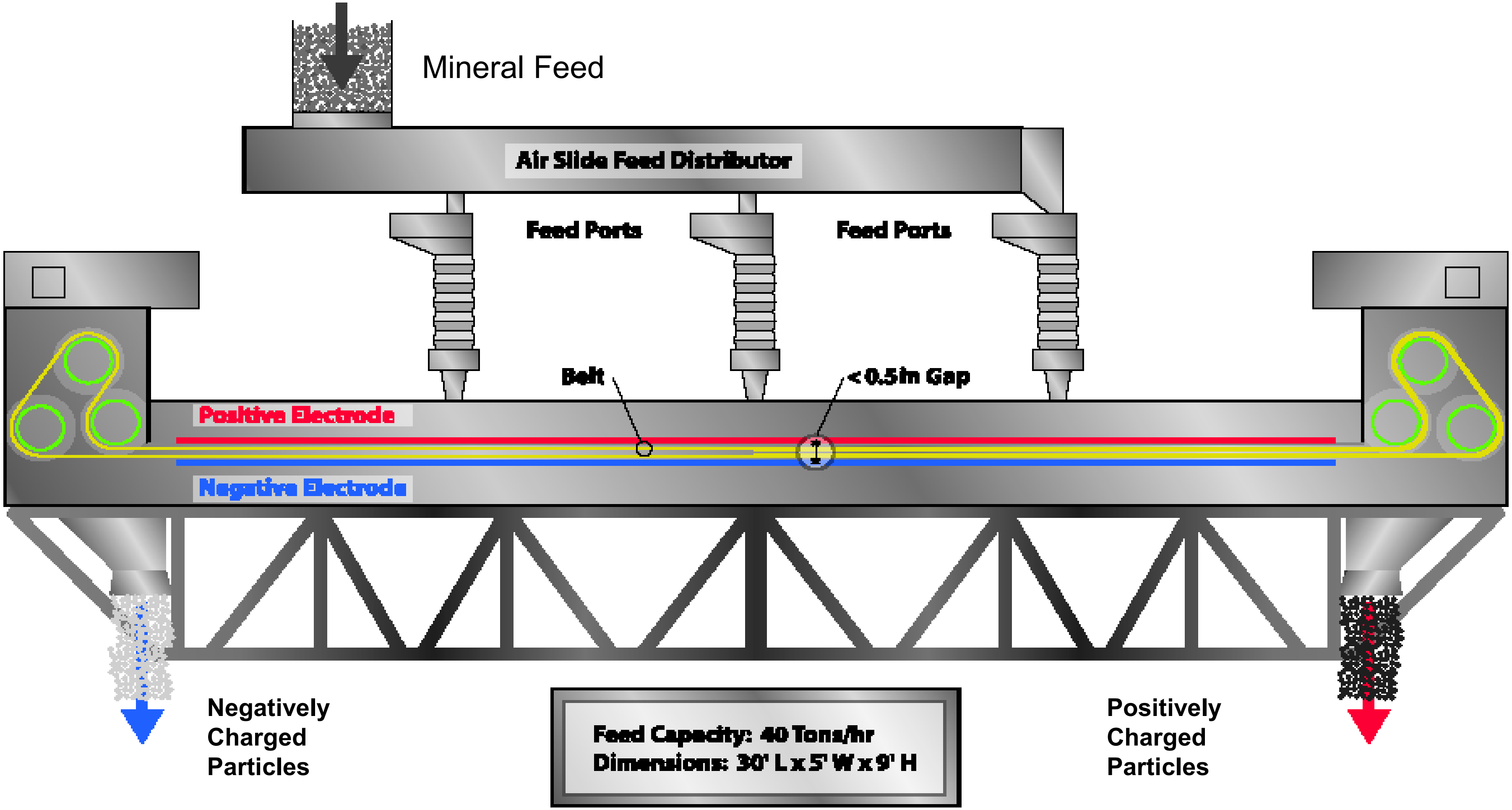
*presenting author

ST Commercial Separator

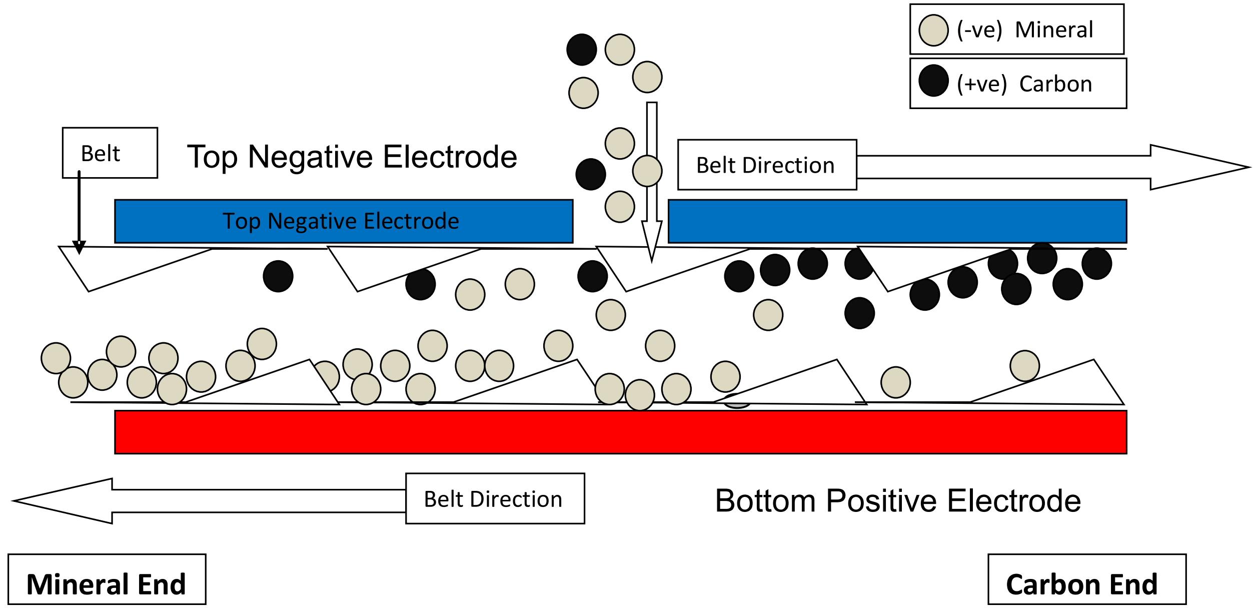


Mass ~10k kg; no mass optimization; 40k kg/hr @40 kW

ST Triboelectrostatic Separator

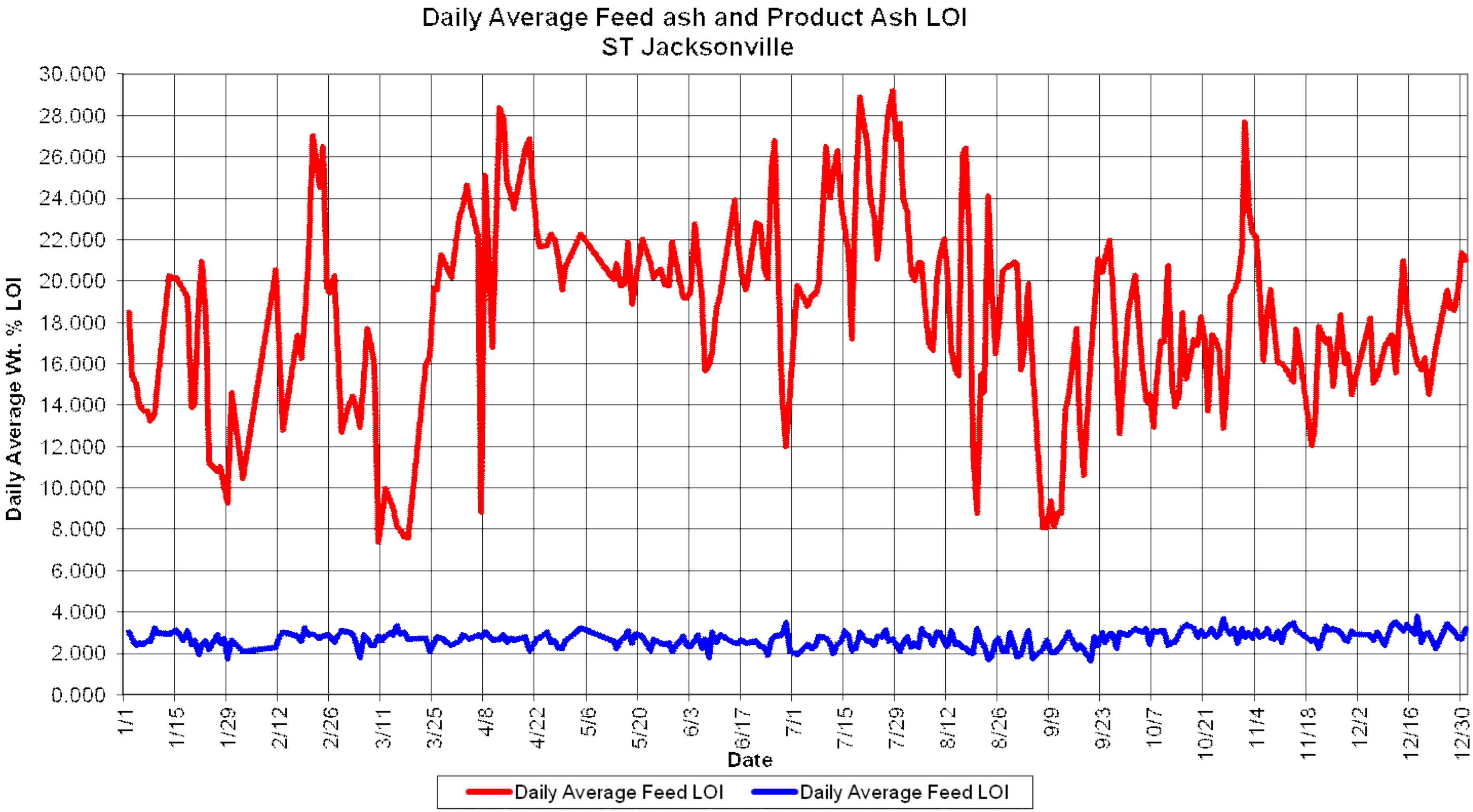


ST Belt Triboelectrostatic Separator



- Small Gap and Vigorous Agitation
- High efficiency multi-stage separation through charging / recharging and internal recycle
- Very low residence times <1 sec
- Particle size range ~500 µm to < 1 µm
- High Capacity 40 tph

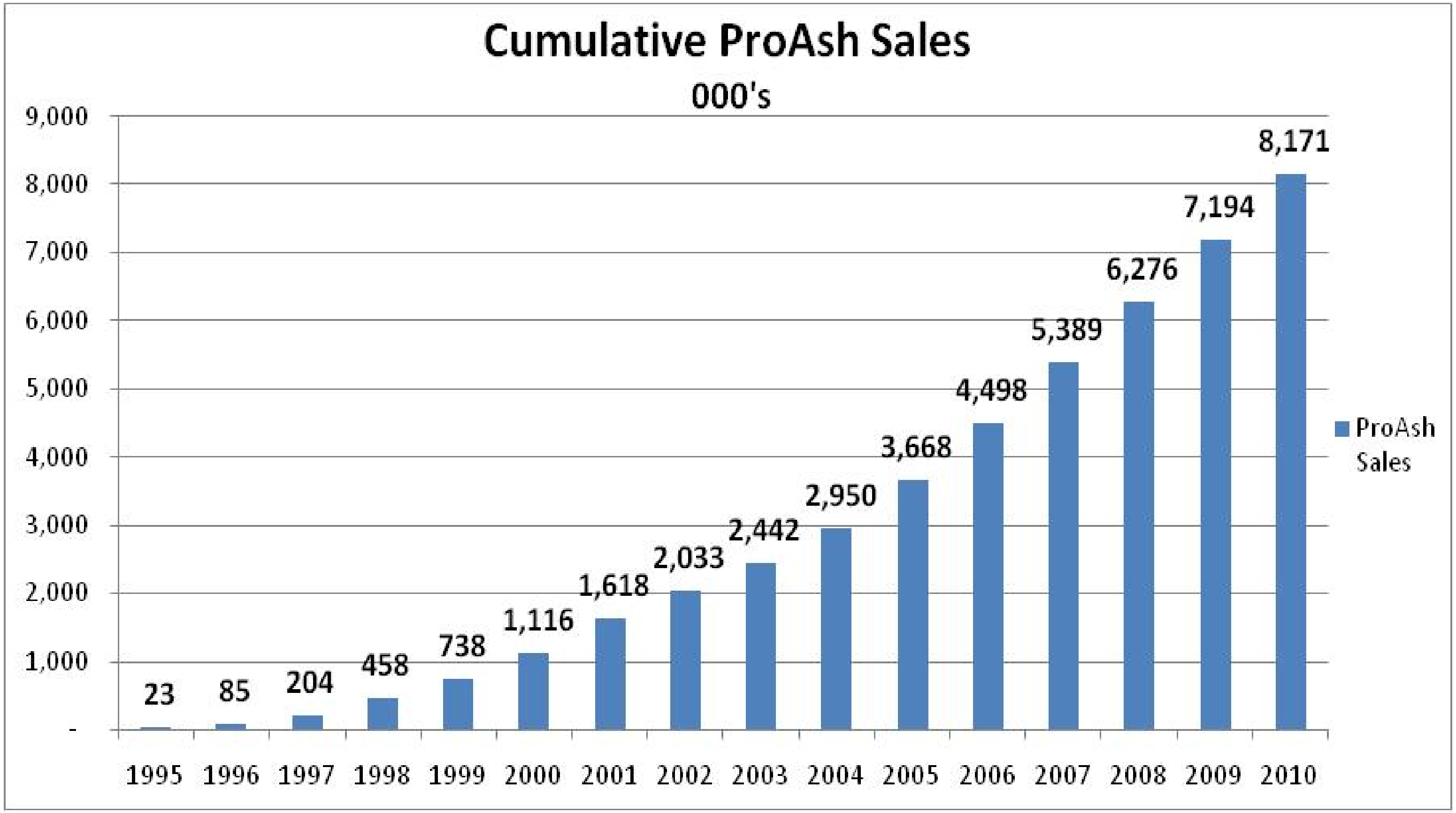
Quality of Low Carbon Fly Ash



ST Separator Process Parameters

- Multiple parameters to adjust separation
  - Feed Point
  - Belt Speed
  - Electrode Gap
  - Electrode Voltage
  - Feed Rate
- Enables consistent low carbon product from highly variable feed material
- Robust Process & Robust equipment

Quantity of Low Carbon Fly Ash



(USA only)

ST Commercial Operations

Plant	Units	Start Yr.	Comments
Progress Energy Roxboro NC	2	1997*	Ongoing operations
CPSG Brandon Shores MD	2	1999/05	Dome + EcoThermTM
Scottish Power Longannet UK	1	2002	Ongoing operations
JEA St John's River FL	2	2003/04	NH3 removal
SMEPA Morrow MS	1	2004	EcoThermTM
NBPower Belledune NB Canada	1	2005	EcoThermTM
RWE Didcot UK	1	2005	EcoThermTM
PP&L Brunner Island PA	2	2007	Dome
TECO – Big Bend FL	3	2008	Dome + NH3 removal
RWE Aberthaw UK	1	2008	NH3 + EcoThermTM
EDF Energy West Burton UK	1	2008	EcoThermTM
ZGP (Lafarge / Ciech) Poland	1	2010	EcoThermTM

*No change over original performance

ST’s Commercial Record

- Twelve Fly Ash plants in U.S., Canada, UK and Poland
- More than 100 separator-years experience on 18 units
- >99% available uptime
- ~ 9,000,000 tons sold (USA only)

Mineral Applications

- ST Separator applicable to any dry mixture of discrete particles
- Differential charging between particles of different surface chemistry - “work function”
- Calcium Carbonate
  - Reduce quartz improve color to increase value
- Talc – Hydrous magnesium silicate
  - Remove magnesite, FeS_2 improve color
- Mined halite / sylvite ore;
  - Separate NaCl and KCl

Contact charging theory

All materials held together by electrons

All materials can be separated (in principle)

Energy e- ~ work function ~ Fermi Energy ~ few volts

Particles collide → Surfaces contact,

@ contact point energy equalized

Delta energy ~ Delta work function

Few volts, few nM gap → electric field ~ 10^9 V/M

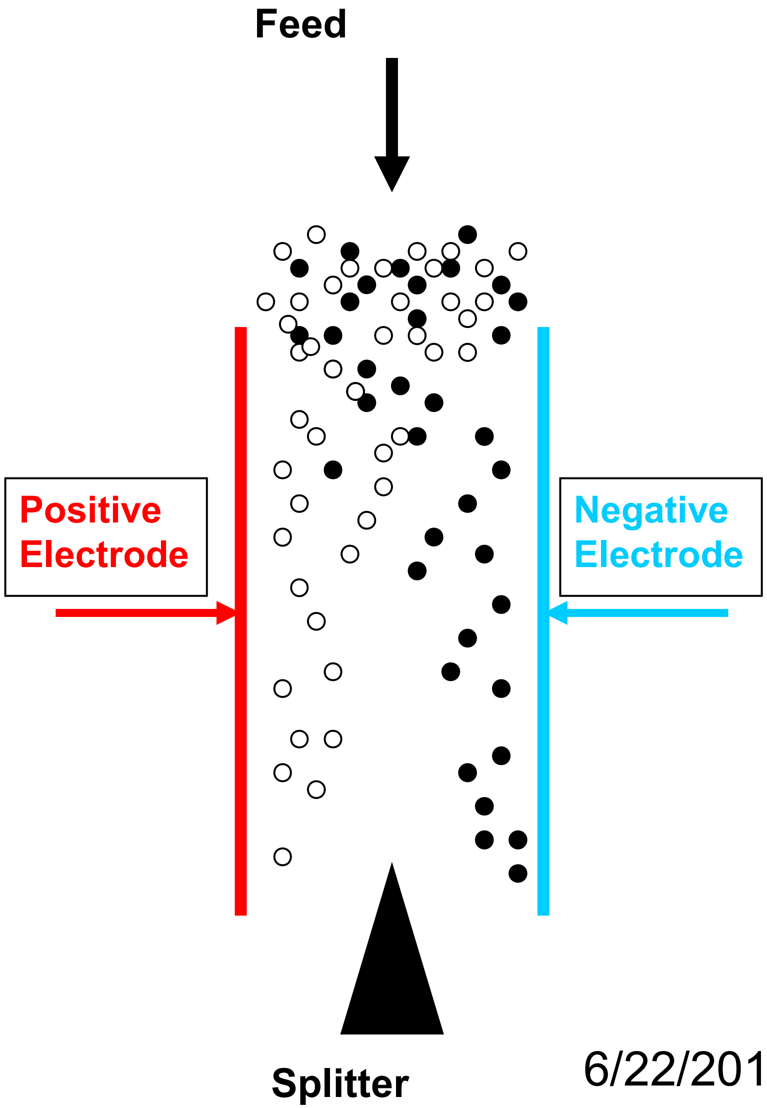
Electron move, equalize energy → E field at surface

Surfaces move apart, charge can't leak back

Low work function materials charge positive

High work function materials charge negative

Free Fall Triboelectrostatic Separator

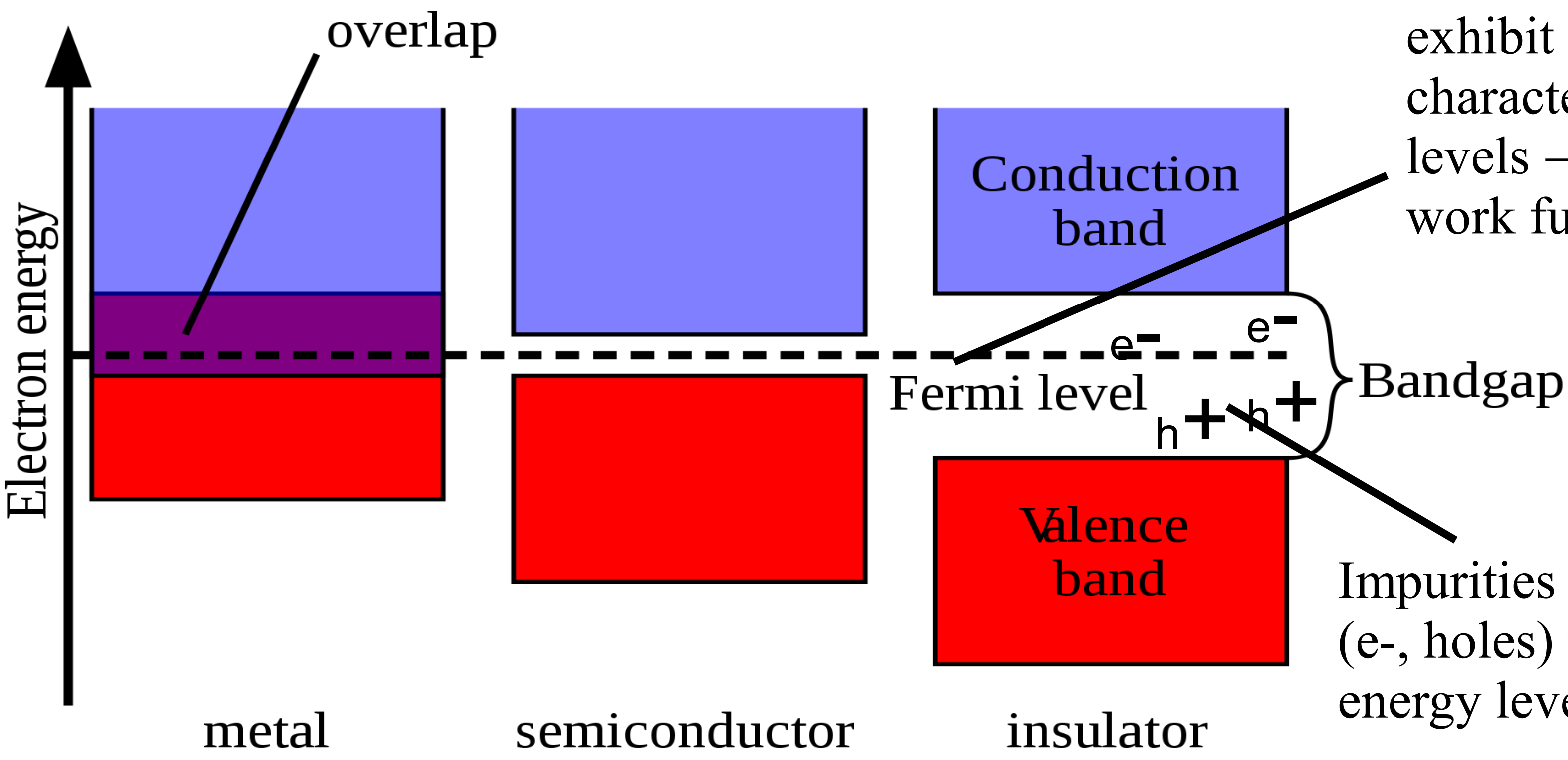


Particles charged by contact in “charger”
Single Stage Separation
If particles stick together → no separation

Large Electrode Gap
Low Particle Loading
Low Throughput / Capacity
Conductive particles reverse charge

<u>Particle Size Effects</u>
Too Large – No Separation
Too Small – Collects on Electrodes
Particle size > 75 µm

Band Theory of Solids



Different materials exhibit different characteristic energy levels → different work functions

Impurities add sites (e-, holes) with discrete energy levels

http://en.wikipedia.org/wiki/File:Isolator-metal.svg (accessed 06/01/2011)

Contact charging mechanisms

Mobile Charge Carriers on surfaces

Type	Positive	Negative
Electronic	Holes	Electrons
Work Function	fewer e-	more e-
Ionic	Cations	Anions
Acid-Base	Protons	Hydroxyl ions
Lewis Acid	e- acceptor	e- donor
Brønsted Acid	H+ donor	H+ acceptor
Redox	Reducing	Oxidizing
Electret	compensated e-	trapped e-

Work Function of the Elements Electron Volts

H																	He
Li 2.93	Be 4.98	Work Function of the Elements Electron Volts										B 4.45	C 5	N	O	F	Ne
Na 2.36	Mg 3.66											Al 4.16	Si 4.73	P	S	Cl	Ar
K 2.29	Ca 2.87	Sc 3.5	Ti 4.33	V 4.3	Cr 4.5	Mn 4.1	Fe 4.74	Co 5	Ni 5.2	Cu 4.82	Zn 4.27	Ga 4.32	Ge	As 3.75	Se 5.9	Br	Kr
Rb 2.26	Sr 2.59	Y 3.1	Zr 4.05	Nb 4.41	Mo 4.66	Tc	Ru 4.71	Rh 4.98	Pd 5.41	Ag 4.63	Cd 4.08	In 4.09	Sn 4.42	Sb 4.63	Te 4.95	I	Xe
Cs 2.14	Ba 2.62		Hf 3.9	Ta 4.4	W 4.77	Re 4.72	Os 5.93	Ir 5.34	Pt 5.53	Au 5.38	Hg 4.48	Tl 4.33	Pb 4.25	Bi 4.35	Po	At	Rn

Electron Affinity of the Elements Electron Volts

H 0.75																	He
Li 0.62	Be	Electron Affinity of the Elements Electron Volts										B 0.28	C 1.26	N	O 1.46	F 3.40	Ne
Na 0.55	Mg											Al 0.43	Si 1.38	P 0.75	S 2.08	Cl 3.61	Ar
K 0.50	Ca 0.02	Sc 0.19	Ti 0.08	V 0.53	Cr 0.68	Mn	Fe 0.15	Co 0.66	Ni 1.16	Cu 1.24	Zn	Ga 0.43	Ge 1.23	As 0.80	Se 2.02	Br 3.36	Kr
Rb 0.48	Sr 0.05	Y 0.31	Zr 0.43	Nb 0.89	Mo 0.75	Tc	Ru	Rh 1.14	Pd 0.56	Ag 1.30	Cd	In 0.38	Sn 1.11	Sb 1.05	Te 1.97	I 3.06	Xe
Cs 0.47	Ba 0.14		Hf	Ta 0.32	W 0.81	Re 1.14	Os 1.08	Ir 1.56	Pt 2.12	Au 2.31	Hg	Tl 0.38	Pb 0.36	Bi 0.94	Po 1.9	At 2.8	Rn

Electrostatic Belt Separator Theory

Contact charging of particles

Particles move in electric field

Belt actively moves particles

Particles moved: contact; charge; separate; repeat

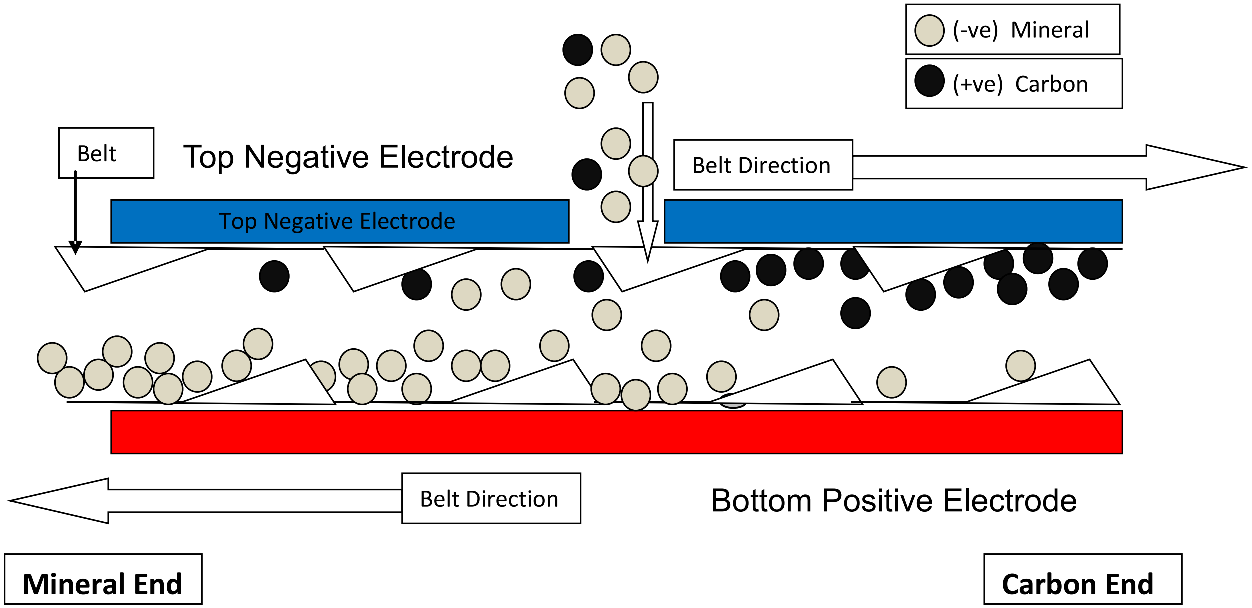
Continuous, multi-stage, counter-current

Universal-type separator, broad PSD,

Independent of gravity (3 orthogonal orientations)

Independent of temperature

ST Belt Triboelectrostatic Separator



- Small Gap and Vigorous Agitation
- High efficiency multi-stage separation through charging / recharging and internal recycle
- Very low residence times <1 sec
- Particle size range ~500 µm to < 1 µm
- High Capacity 40 tph

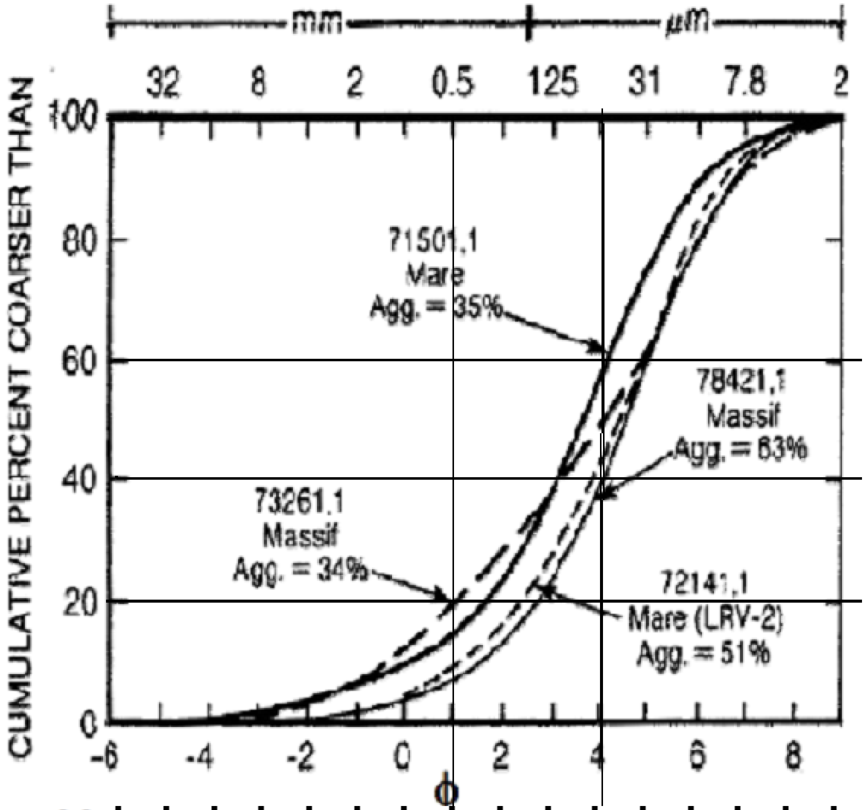
Belt Separator: Benefits In Space

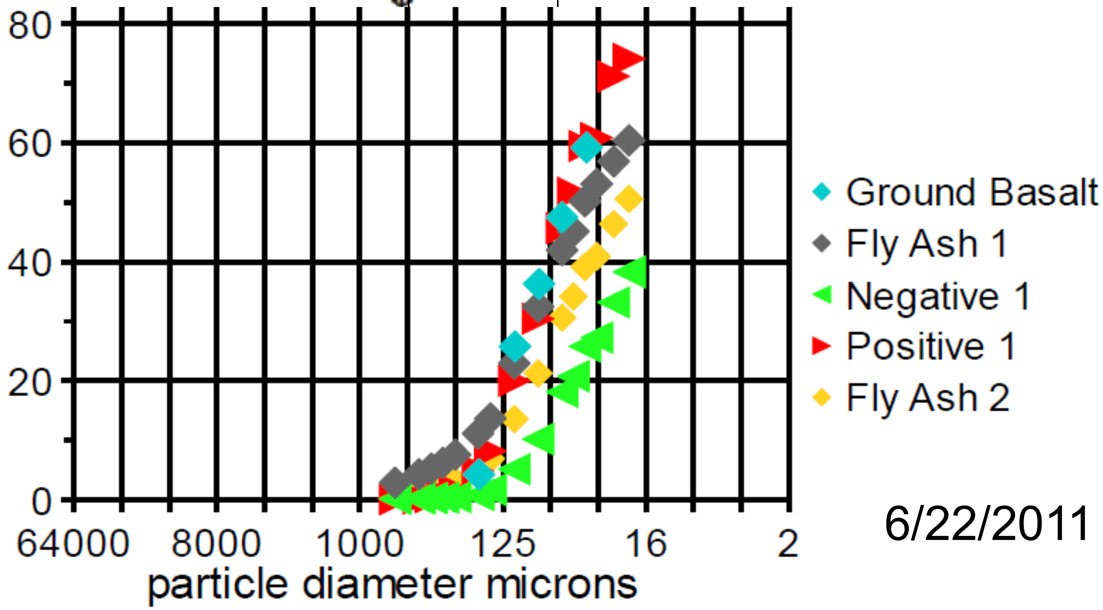
Low power: ~1 kwhr/ton

Low mass: Process ~ 50x mass / hour

Universal type separator

- Contact Charging → universal property
- Gravity Independent → (3 ⊥ orientations)
- Conductive / non-conductive
- Fine particles >500 µm to <1 µm
- Temperature independent





- Fly Ash finer than Regolith
- Sieving only needed on top size
- Coarse sieving much easier than fine sieving.
- PSD is of basalt used in ice/basalt separation

PSD basalt & fly ash via sieving

PSD Regolith from Apollo 17 soil 78221,8,NASA In-Situ Resource Utilization (ISRU) Research & Development, Sanders, GB et al., Oct. 2006, Gerald. B Sanders/ JSC, gerald.b.sanders@nasa.gov

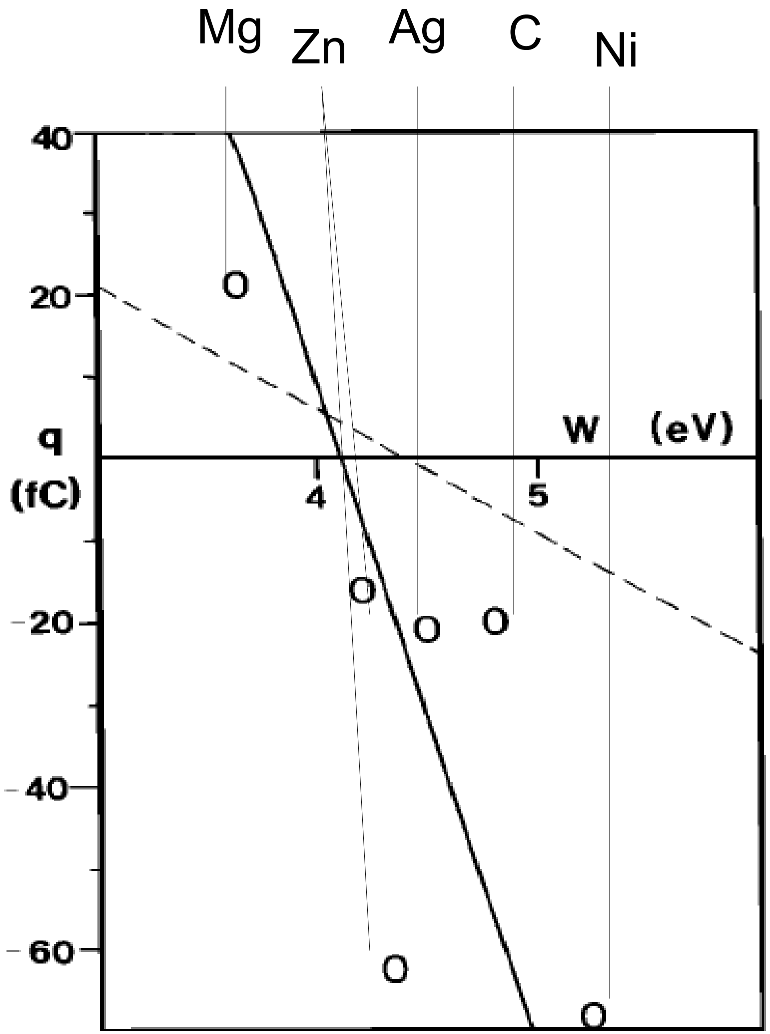


Fig. 5. Average charge transfer (q) at $-10°C$ of 100-μm ice spheres plotted against the work function (W) of the target. Solid line, least squares fit; dotted line, *Buser and Aufdermaur* [1977] for 20-μm spheres at $-45°C$.

Contact charging of ice against metals: Indicates work function slightly higher than Mg.

Caranti, J. M., Illingworth, A. J., and Marsh, S. J.: The Charging of Ice by Differences in Contact Potential, J. Geophys. Res. D 90, 6041–6046, 1985

Ice from Basalt separation

	100%	67.5%	32.5%
(dry basis)	Feed basalt	Positive charging	Negative Charging
SiO_2	43.5	39.2	46.7
TiO_2	6.96	10.61	5.22
MnO	0.2	0.26	0.2
MgO	6.45	7.32	7.06
Al_2O_3	12.76	9.5	12.96
Fe_2O_3	18.2	25.11	16.5
K_2O	0.21	0.16	0.23
Na_2O	2.28	1.61	2.32
CaO	11	10.54	12.17
Basalt	**50.00**	**14**	**83**
H_2O (ice)	**50.00**	**86**	**17**

- Minnesota basalt gathered as massive pieces, broken to minus 2 inch, crushed to minus 1/4 inch in jaw crusher, ground in ceramic faced disk mill (in air).
- Cooled in LN2 as slurry
- Water frozen @ -25ºC in ice cube trays, cooled in LN2, ground in Waring blender.
- Basalt in LN2 slurry added
- Ice/basalt slurry mixed
- LN2 allowed to evaporate
- Dry powder fed into separator at about -100ºC

Ice from Basalt separation

Normative minerals (element balance)			
(dry basis) normative	Feed basalt	Positive charging	Negative Charging
Ilmenite	13.22	20.15	9.91
anorthite	25.64	19.39	25.97
orthoclase	1.22	0.92	1.35
Albite	16.53	11.7	16.81
enstatite	9.21	6.72	11.84
FeSiO3	9.57	8.33	11.09
CaSiO3	12.08	13.73	14.36
MnSiO3	0.37	0.47	0.37
Forsterite	4.8	8.07	4.03
Fayalite	6.95	11.69	5.83
Olivine	11.75	19.76	9.86
Sum	99.59	101.68	101.56

- Minerals charge positively and separate along with ice.
  - Olivine
  - Ilmenite
- Minerals that charge negatively and separate from ice
  - Anorthite
  - Orthoclase
  - Albite
  - Enstatite
  - Metallic Iron (data not shown)
- Minerals that should separate
  - H_2O_2, nitrates, peroxides
  - Perchlorates, CO_2, O_2, NH_3
  - ???

Electrostatic Belt Separator Theory

- Deceptively simple
- Commercial practice on fly ash, minerals
  - Process extremely robust
  - Detailed theory of operation not needed Fly Ash
- Data on separation of ice from ground basalt
  - It works!
  - But better theory would be valuable
  - More robust process, equipment, control
  - Untapped degrees of freedom
- Implications lunar operation, Mars

ST Separator Process Parameters

- Mechanism(s) by which some parameters modify separation remains unknown, e. g.
  - Belt Speed
  - Electrode Gap
  - Electrode Voltage
  - Feed Rate
- Experience → very robust and reliable on Earth
- Reliable on Moon? In vacuum?
  - Materials/equipment reliability?
  - Process reliability?

ST & Titan Corporate Capabilities

- Unique Expertise in Belt Separators
  - World's *(only)* experts in belt separators
- Separator Design, Build, Operate,
  - Remote operate, Close-loop operate
- World-wide technical support via Internet,
  - Remote monitor, operate
- Facilities for testing (at ambient)
  - No substitute for machine time hours
  - Hundreds, thousands, tens of thousands
  - Robust Equipment → Robust Process

How to address Lunar opportunity?

- **Need Robust Process & Equipment**
- **Requires cryogenic and vacuum R&D**
  - **No commercial applications**
- **Equipment & Process R&D**
- **Equipment durability testing**
- ***Enabling technology for lunar ice***
  - ***Other lunar minerals?***
- **How to get there from here?**