Ore Sorting Technologies and Applications in the Coal

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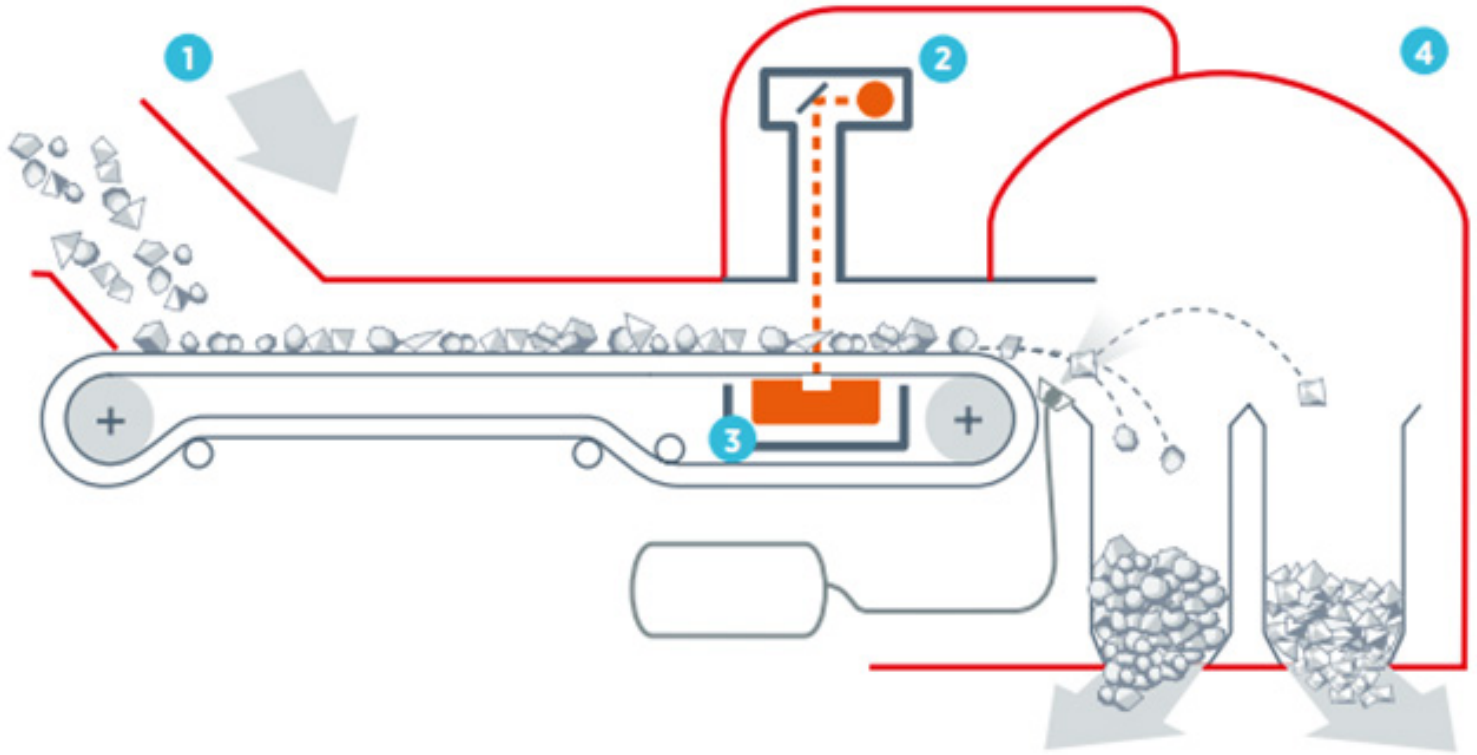
Cleaning Coal at the Speed of Light

- Hand sorting was historically a common practice for ores and coal.
- First radiometric sorter in 1946.
- Photometric sorter developed in 1952 was the basis of the first commercial sorters in uranium.
- Around 35 ore sorters worldwide in 1990.
- Estimated 300 plus/minus sorters in 2009.

*Mineral Separation Technologies, Inc.

Typical Sorting Process

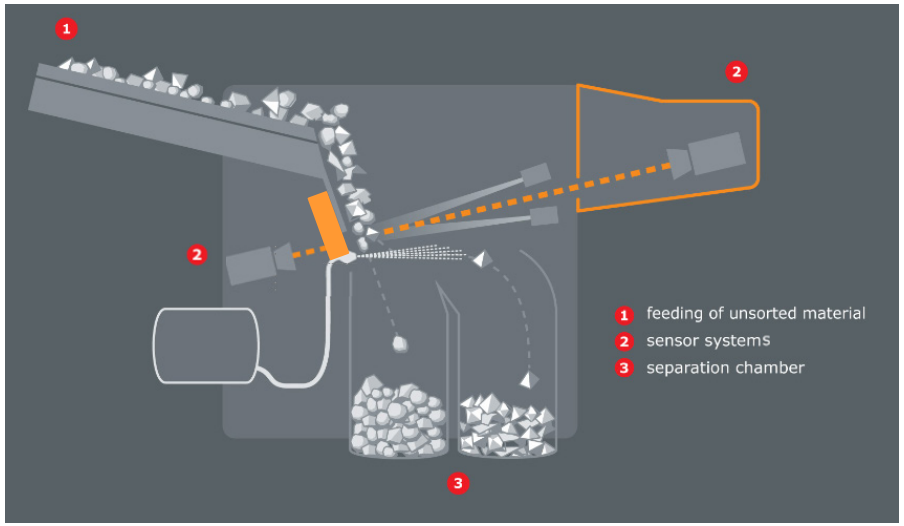
- Process involves the following sequential steps:
  - Particle Presentation
  - Particle Examination
  - Data Analysis
  - Particle Separation

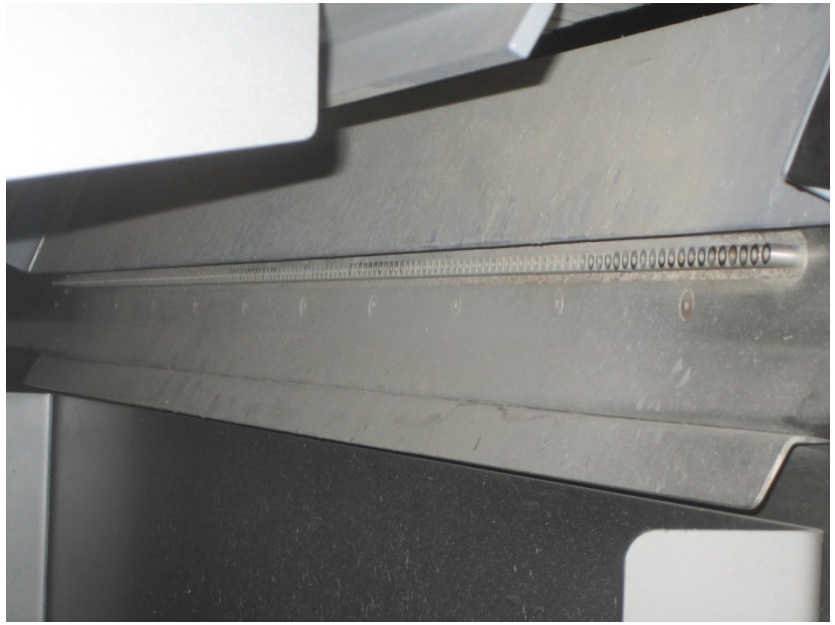


* Tomra Sorting Solutions

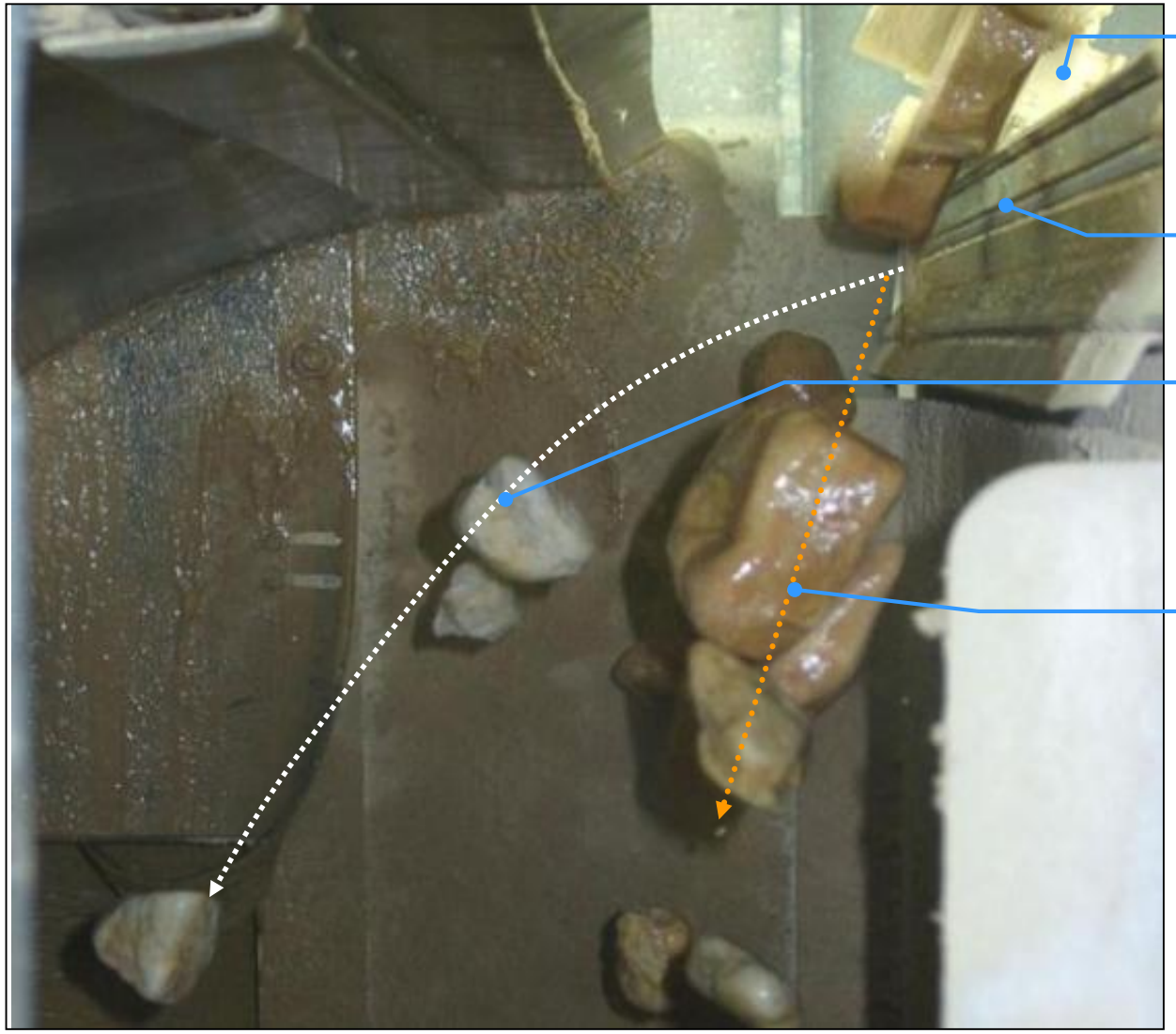
Ore Sorting

- Achieves a separation using a sensor, computer and air jets.
- Sensors are:
  - Optical
  - X-Ray
  - Electromagnetic
  - Infrared
  - Lazer
- Multiple sensors can be used.
- 450 air nozzles on a 2 meter wide unit.
- Particle sizes from 100 x 10 mm
- Particle surface can be moist.





Sorting Quartz Pebbles (100 x 20 mm)



Feed stream on chute

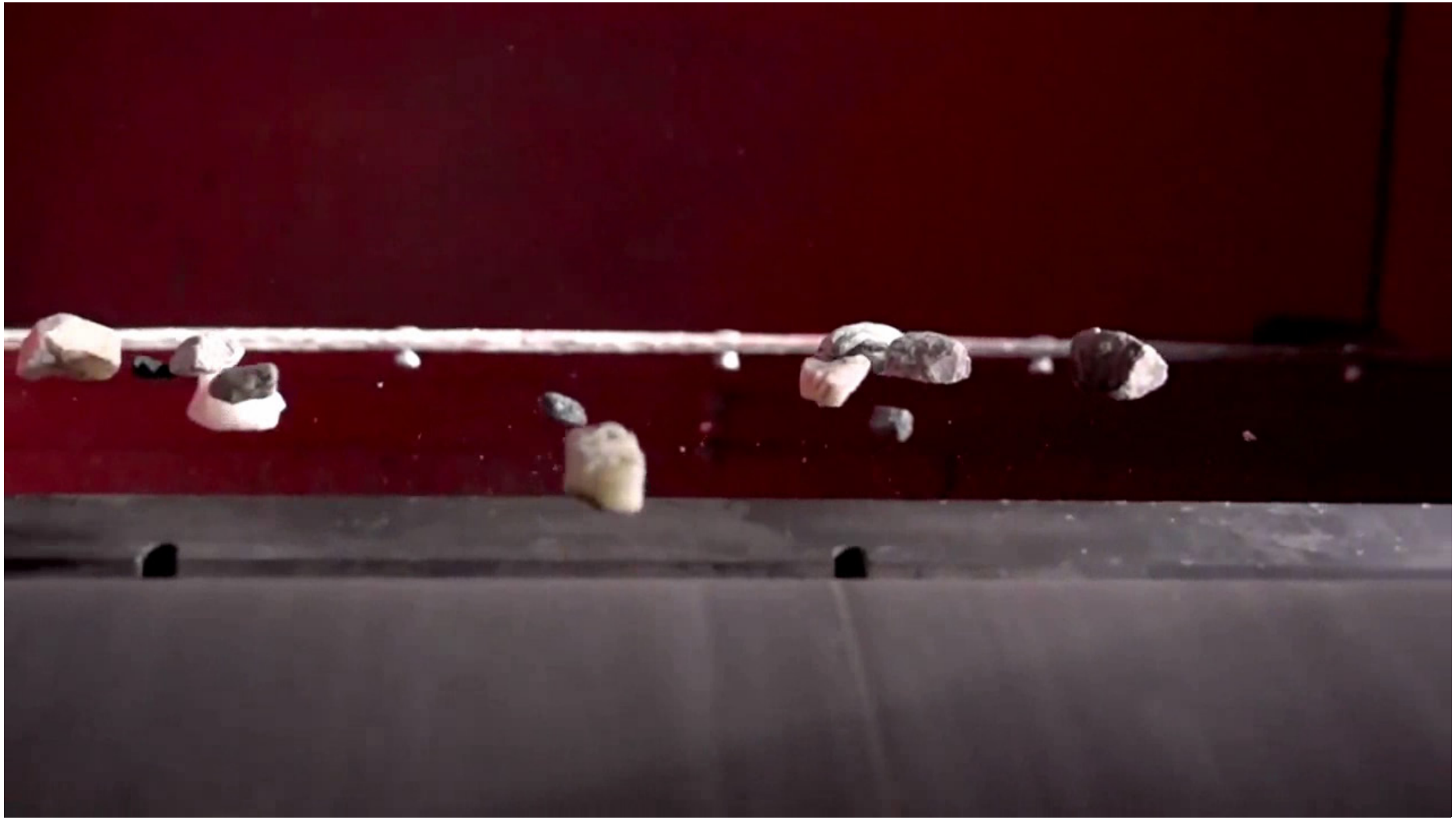
Nozzle bar

Trajectory of ejected material

Trajectory of accepted material

* Tomra Sorting Solutions

Ore Sorting Video



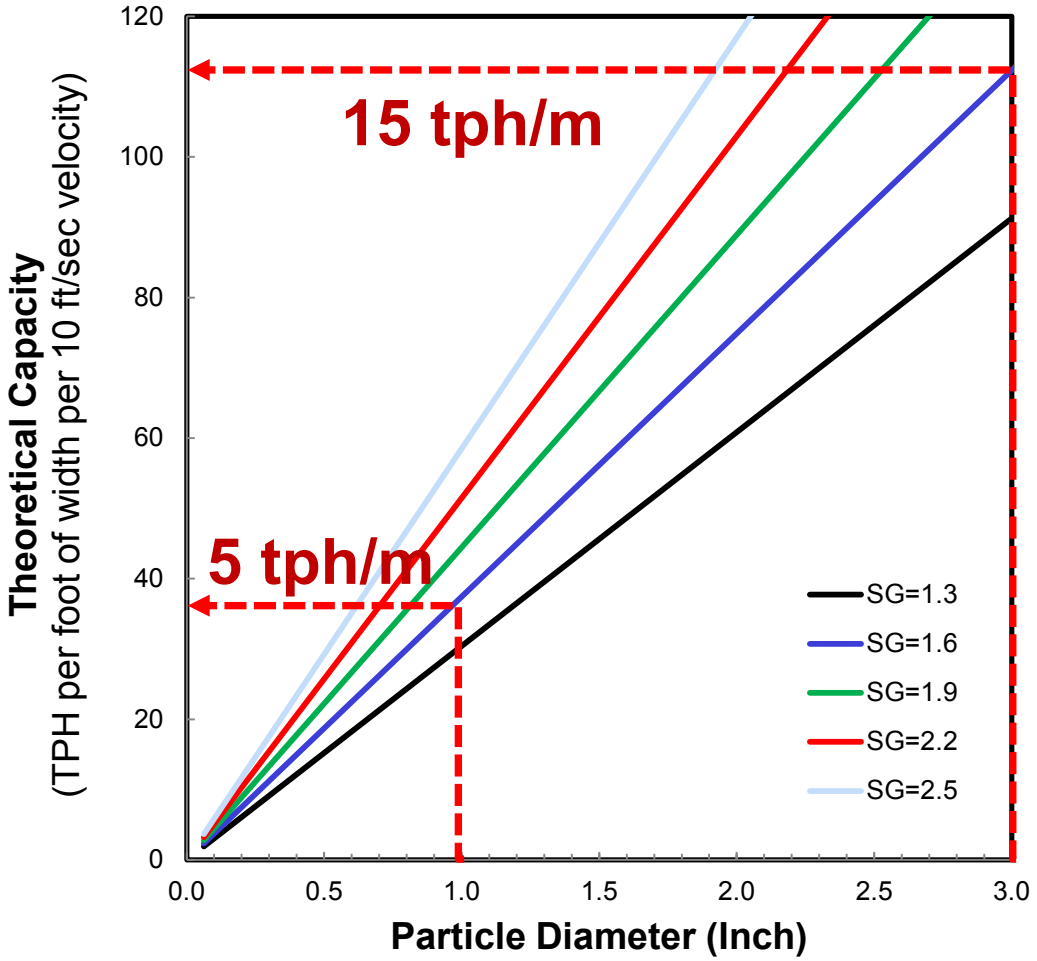
STEINERT
MAGNETIC + SENSOR SORTING SOLUTIONS

Sorter Capacity

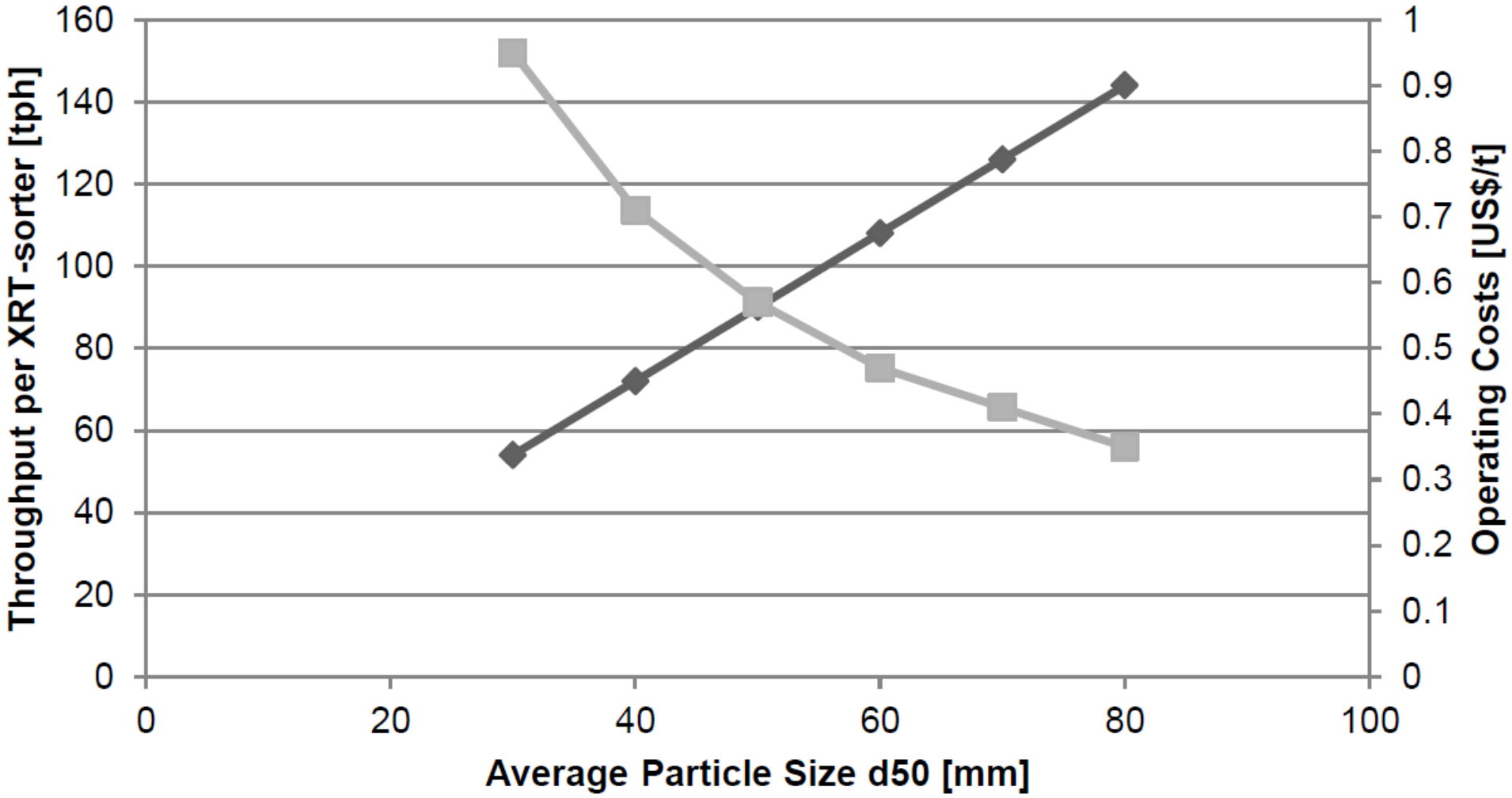
$$Q = W \times Dp \times V \times \beta$$

$$M = \rho \times Q$$

M	= mass flow rate
Q	= volumetric flow
W	= machine width
D_p	= particle diameter
V	= belt velocity
β	= packing (<$\pi/6$)



Typical Sorting Capacity & Operating Cost



*Tomra Sorting Solutions (February 2013 report)

Ore Sorting Applications

	INDUSTRIAL MINERALS	BASE & Fe METALS	FUEL/ ENERGY	PRECIOUS METALS	DIAMONDS & GEMS	METAL SLAG
COMMODITY	• Calcite • Quarts • Feldspar • Magnesite • Talcum • Dolomite • Salt	•Copper • Zinc • Nickel • Tungsten • Iron • Manganese • Chromite	• Coal • Uranium	• Gold • Platinum	• Diamonds • Tanzanite • Colored gemstones	• Stainless steel • Copper • Chrome
SENSOR TECHNOLOGY	COLOR XRT NIR XRF	XRT COLOR EM NIR	XRT RM	XRT COLOR XRF NIR	COLOR XRT XRF NIR	XRT XRF EM

Calcite | Copper | Coal | Gold | Diamonds | Ferro Silica Slag

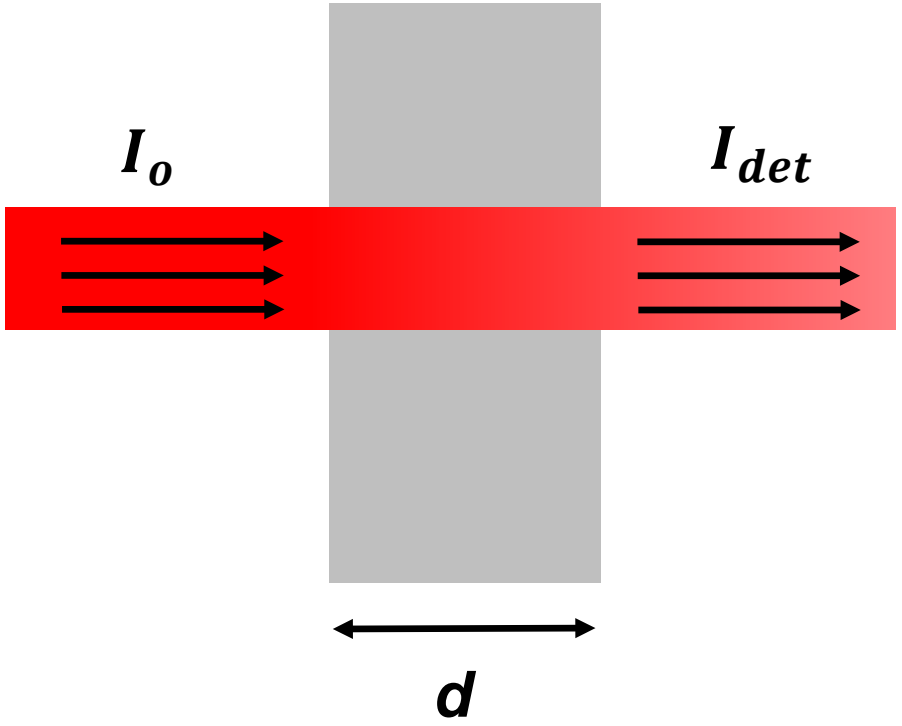
* Tomra Sorting Solutions, 2014

X-Ray Transmission

- X-rays are transmitted the materials at varying degrees according to atomic density.
- Lambert's Law:

$$I_{det} = I_o e^{-\mu(\lambda)\rho d}$$

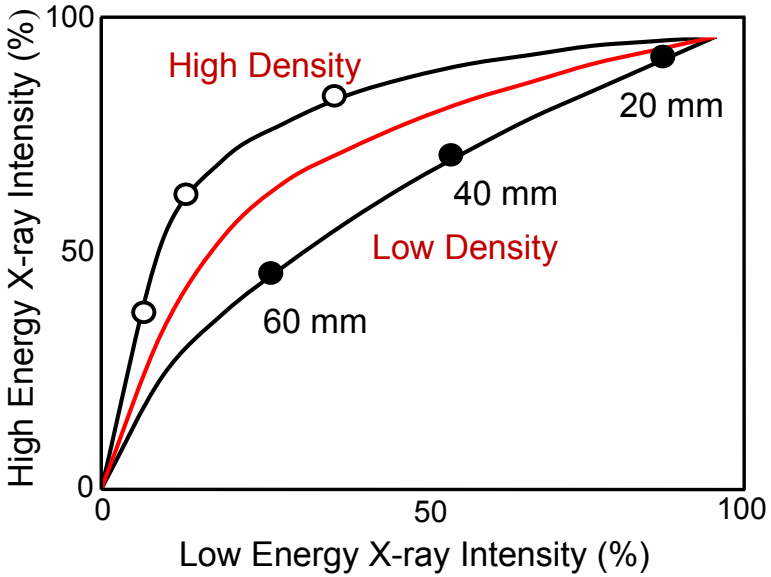
ρ = particle density
d = particle size
$\mu(\lambda)$ = mass adsorption coefficient



- Mass adsorption co-efficient is specific to the elements within the solid mass.

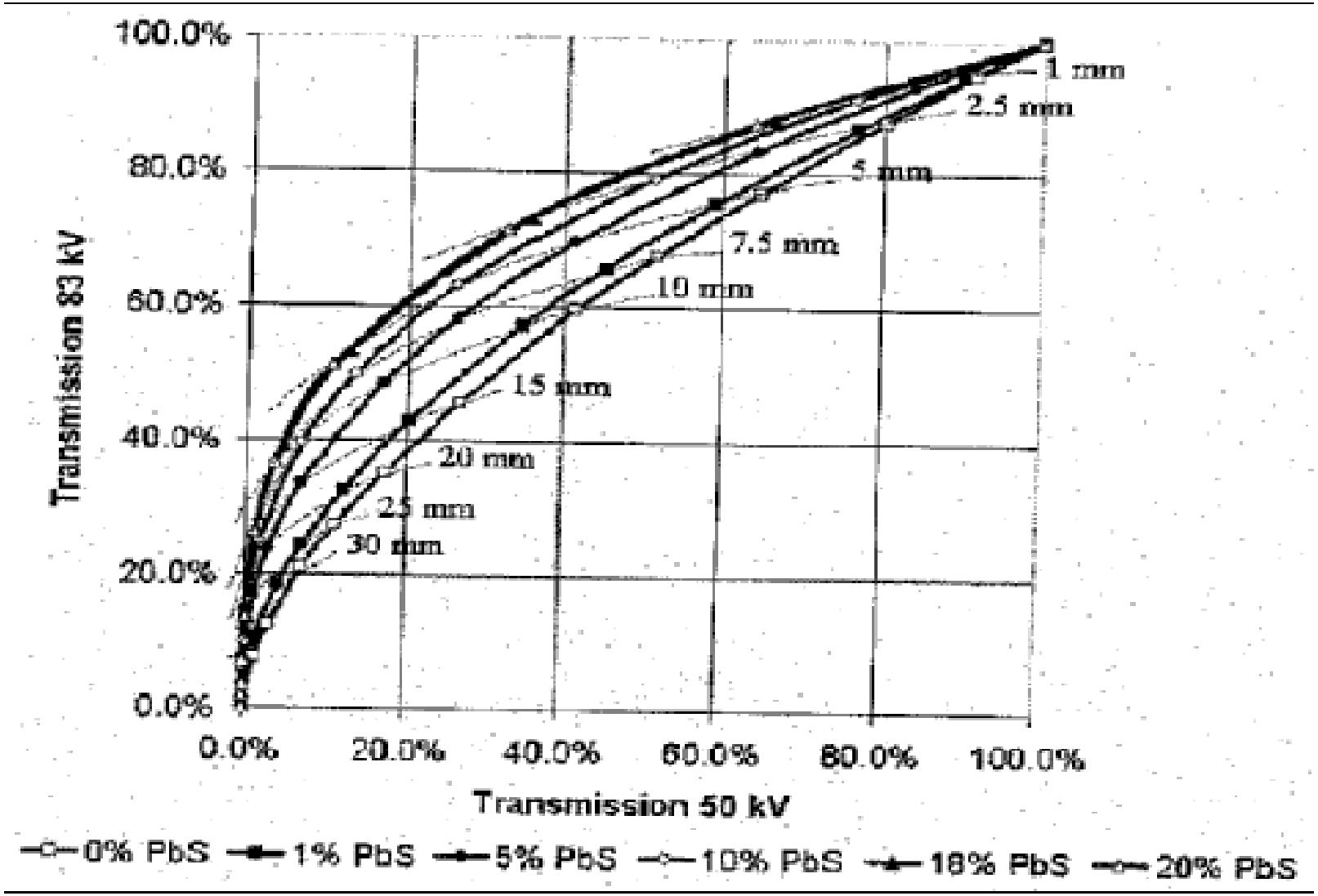
Dual Energy XRT Separations

- The transmission of a single energy wave is strongly influenced by particle size.
- To provide separations over a range of particle sizes:
  - a dual energy x-ray can be applied.
  - Combination of x-ray and a lazer for size detection.
- Subjecting a composite particle having a range of sizes to a high and low energy x-ray results in transmission curves.



Particle Size-by-Density Samples

Dual Energy XRT Separations

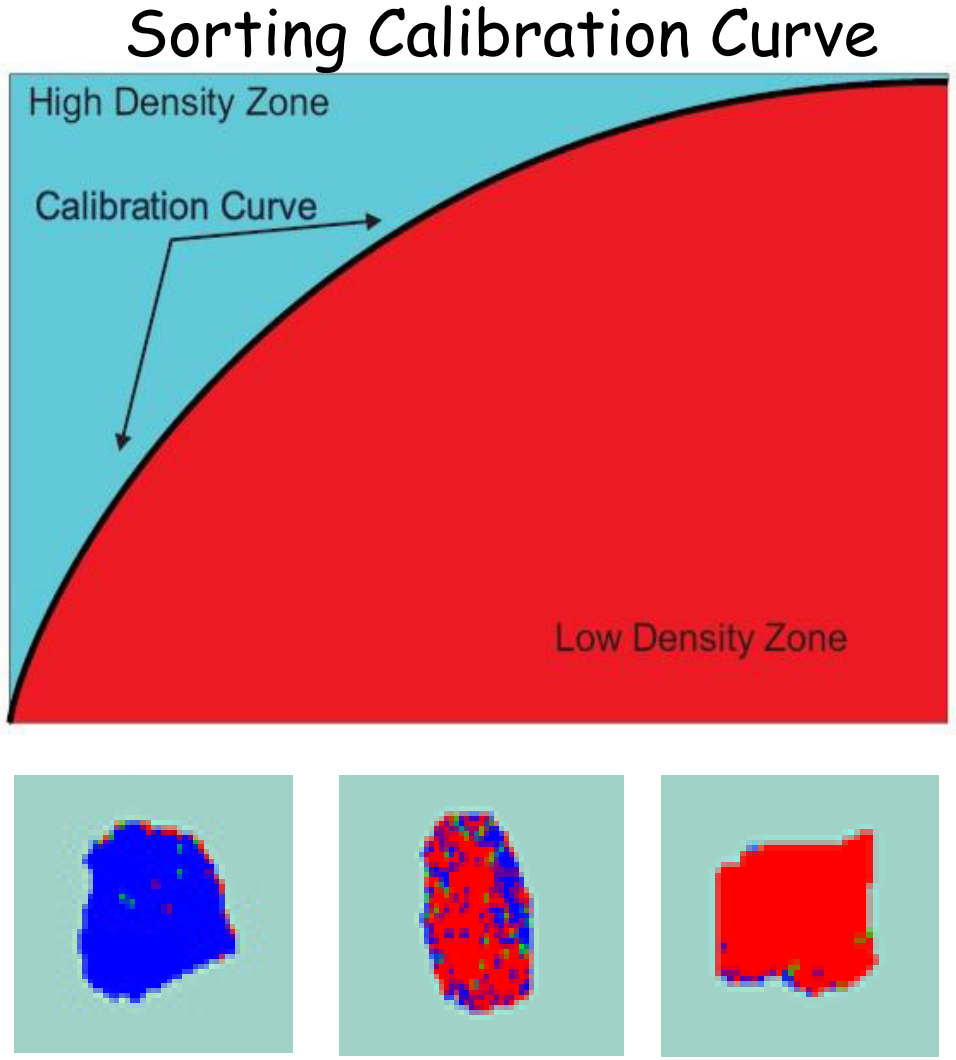


*De Jong and Harbeck (2005)

X-Ray Image of U.S. Bituminous Coal

Dual Energy XRT Sorting

- Representative samples of the material needed by sorted are subjected to XRT analysis based on the calibration curve.
- The image generated is divided into pixels and the pixels colored according to the location above or below the calibration curve.
- Selection criteria is established based on the % of pixels colored in blue or red.

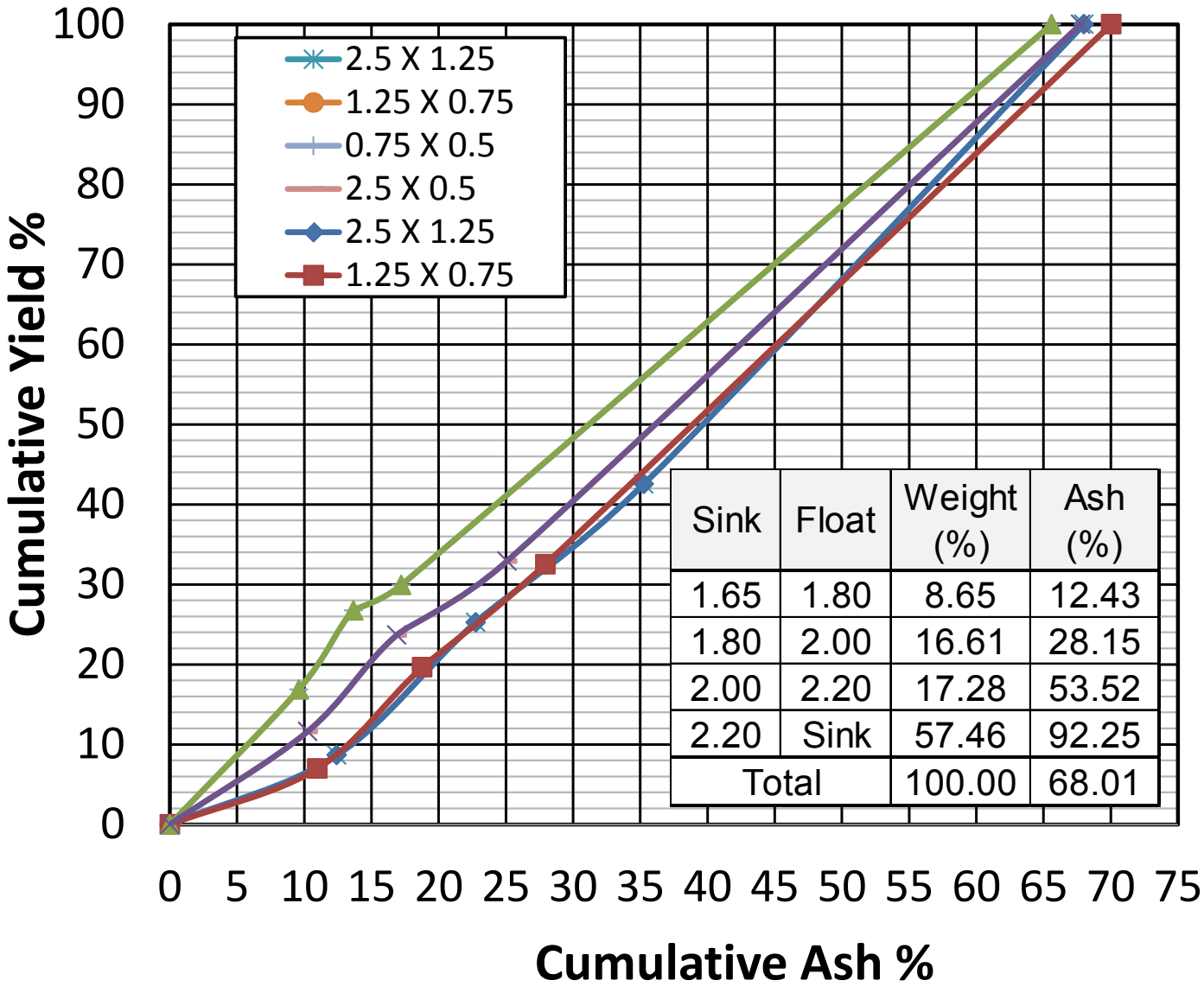


*H. Strydom, 2010

Application: High Ash Content Anthracite

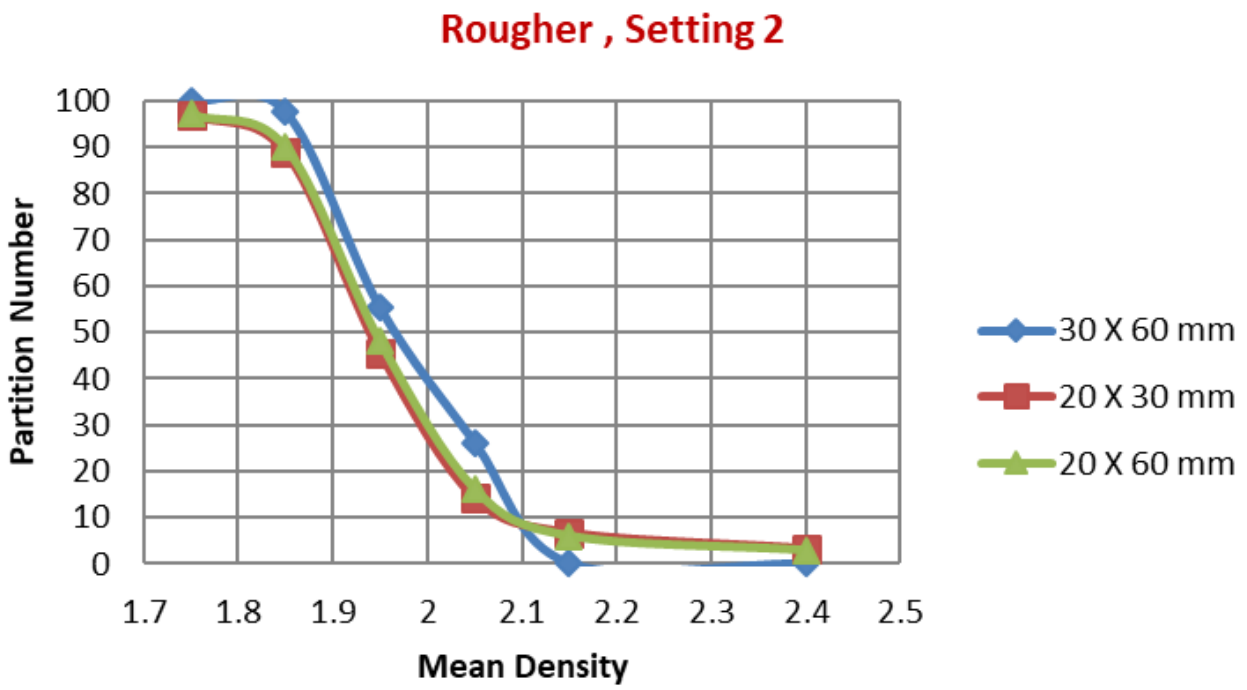
- 60 x 20 mm Anthracite
- Primary goal was to avoid wet-based process due to a highly fractured and friable coal and limited water supply.
- Very difficult washability characteristics.
- Tomra Sorting Solutions test facility in Wedel, Germany
- Tests conducted at a throughput capacity of 70 tph
- Three SG cutpoint test settings evaluated.

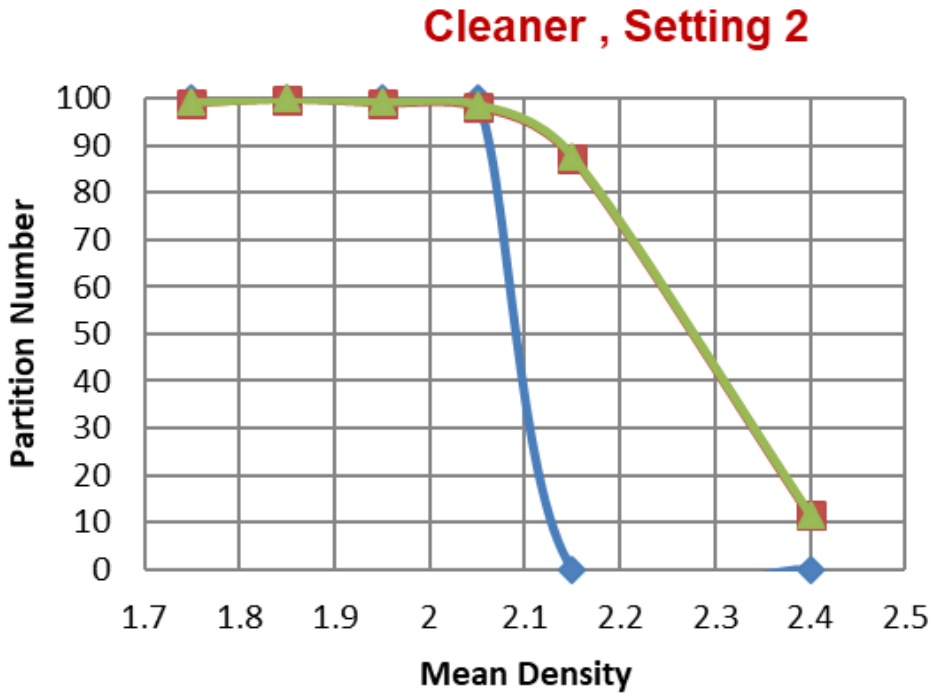
Feed Washability



Sink	Float	Weight (%)	Ash (%)
1.65	1.80	8.65	12.43
1.80	2.00	16.61	28.15
2.00	2.20	17.28	53.52
2.20	Sink	57.46	92.25
Total		100.00	68.01

Partition Curves





Single State Performance Results

Feed Ash = 68.01%

Density Cutpoint Setting	Size Fraction	Product Yield %	Product Ash %	Organic Efficiency %	Product Bypass %	Reject Bypass %	Ep	Sp. Gr. Cutpoint
Setting 1	30 x 60 mm	13.10	13.81	97.04	0	0	0.065	1.91
	20 x 30 mm	13.45	17.10	61.14	4.23	1.41	0.055	1.87
	20 x 60 mm	13.72	16.53	65.33	3.62	1.17	0.06	1.88
Setting 2	30 x 60 mm	18.19	16.99	90.96	0	0	0.07	1.97
	20 x 30 mm	20.02	22.45	71.51	3.05	3.29	0.06	1.94
	20 x 60 mm	20.12	21.65	80.48	2.72	2.87	0.06	1.94
Setting 3	30 x 60 mm	24.55	24.98	90.93	6.17	2.53	0.08	2.25
	20 x 30 mm	28.75	30.1	73.72	3.48	7.47	0.07	2.14
	20 x 60 mm	28.73	29.36	73.66	3.68	6.71	0.12	2.17

- Rougher stage ejected the low density particles due to the low weight percent in the lower specific gravity fractions.

Cleaner Performance Results

Feed Ash = 68.01%

Density Cutpoint Setting	Size Fraction	Product Yield %	Product Ash %	Organic Efficiency %	Product Bypass %	Reject Bypass %	Ep	Sp. Gr. Cutpoint
Setting 1	30 x 60 mm	100	13.81	100	0	0	0.02	2.09
	20 x 30 mm	92.69	12.38	99.67	1.10	14.92	0.105	2.24
	20 x 60 mm	94.19	12.69	99.15	0.93	15.32	0.105	2.25
Setting 2	30 x 60 mm	100	16.99	100	0	0	0.02	2.09
	20 x 30 mm	88.95	15.46	99.94	0.96	11.39	0.08	2.27
	20 x 60 mm	90.65	15.61	99.62	0.85	11.67	0.105	2.25
Setting 3	30 x 60 mm	90.05	21.97	98.95	0	17.59	0.125	2.23
	20 x 30 mm	81.98	20.24	98.77	1.73	13.26	0.075	2.29
	20 x 60 mm	84.01	20.52	98.86	1.44	14.15	0.085	2.23

- Cleaner stage ejected the higher density particles from the rougher stage product.

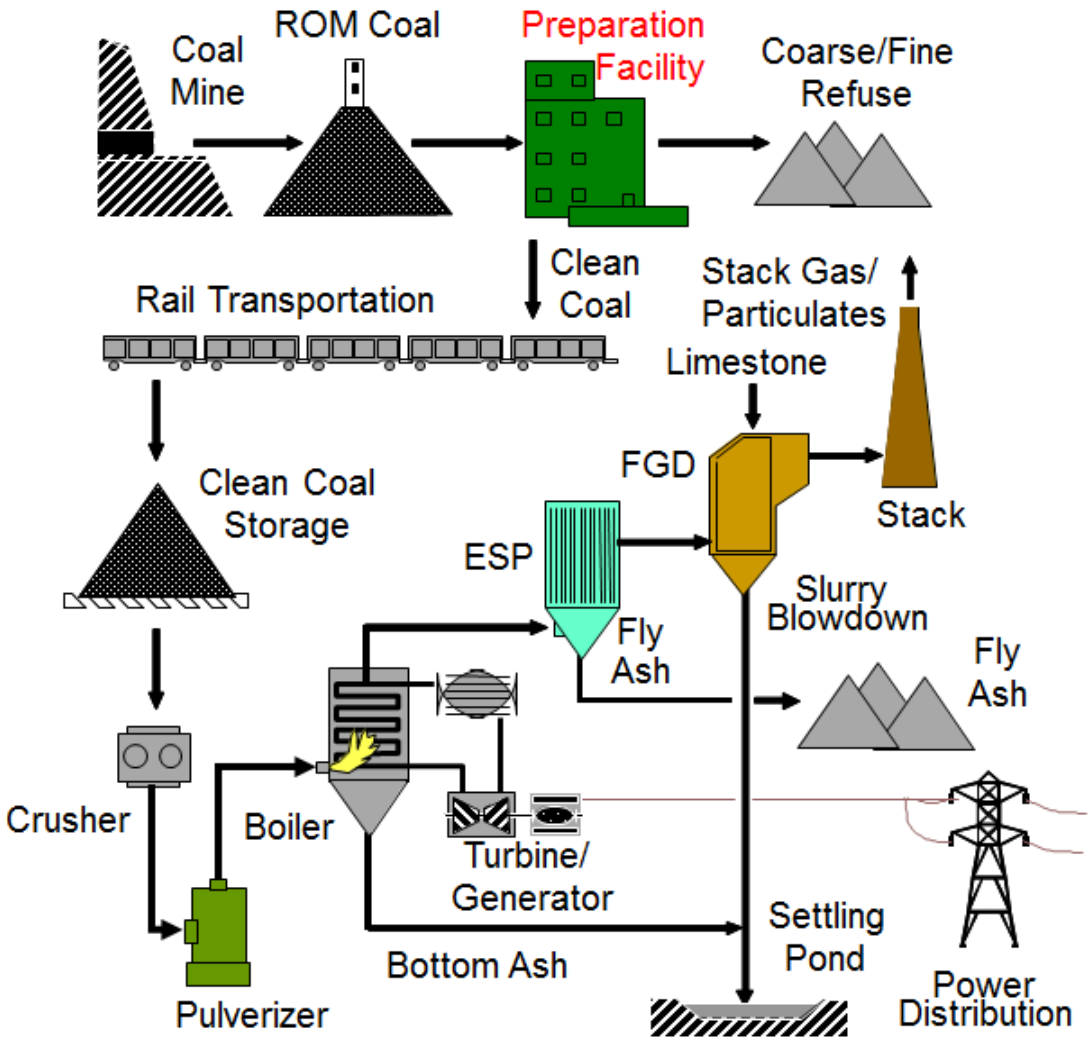
60 x 20 mm Rougher-Cleaner

Performance Parameter	Setting No. 1	Setting No. 2	Setting No. 3
Feed Ash (%)	71.35	69.86	70.41
Product Ash (%)	12.69	15.61	20.52
Cleaner Tailings Ash (%)	81.74	84.00	82.65
Rougher Tailings Ash (%)	79.87	81.78	86.46
Mass Yield (%)	12.93	18.00	24.34
Recovery (%)	39.39	50.42	65.39
Cutpoint	1.88	1.94	2.11
Ep	0.06	0.06	0.11

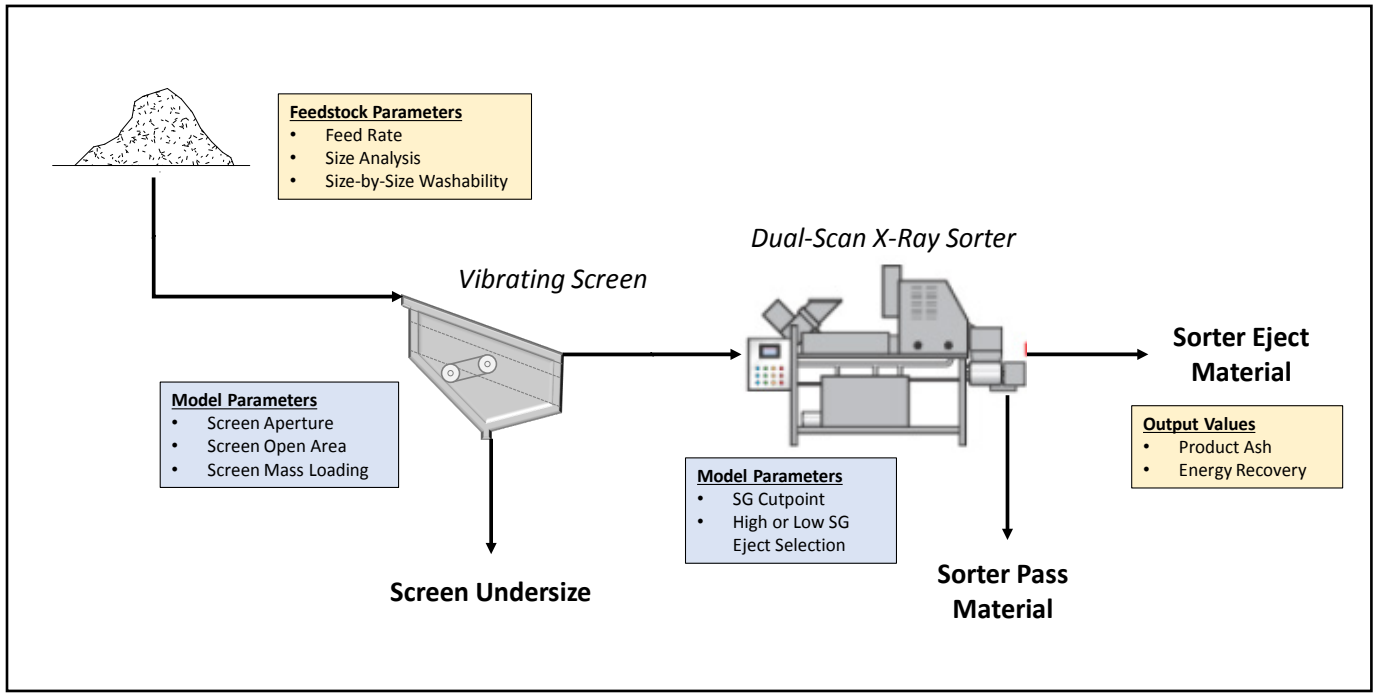
- Cleaner stage ejected the higher density particles from the rougher stage product.

Application: Upgrading Utility Coal Feedstock

- In some cases, ROM coal is directly shipped to utilities and possibility blended to achieve an expectable feedstock.
- Variability due to mining conditions typically results in more or less rock in the ROM coal.
- Sorter units provide a high capacity, low expense option to achieve a more consistent quality which positively impacts:
  - Pulverizer & boiler downtime
  - Boiler efficiency
  - Emissions
  - Waste handling costs, etc.



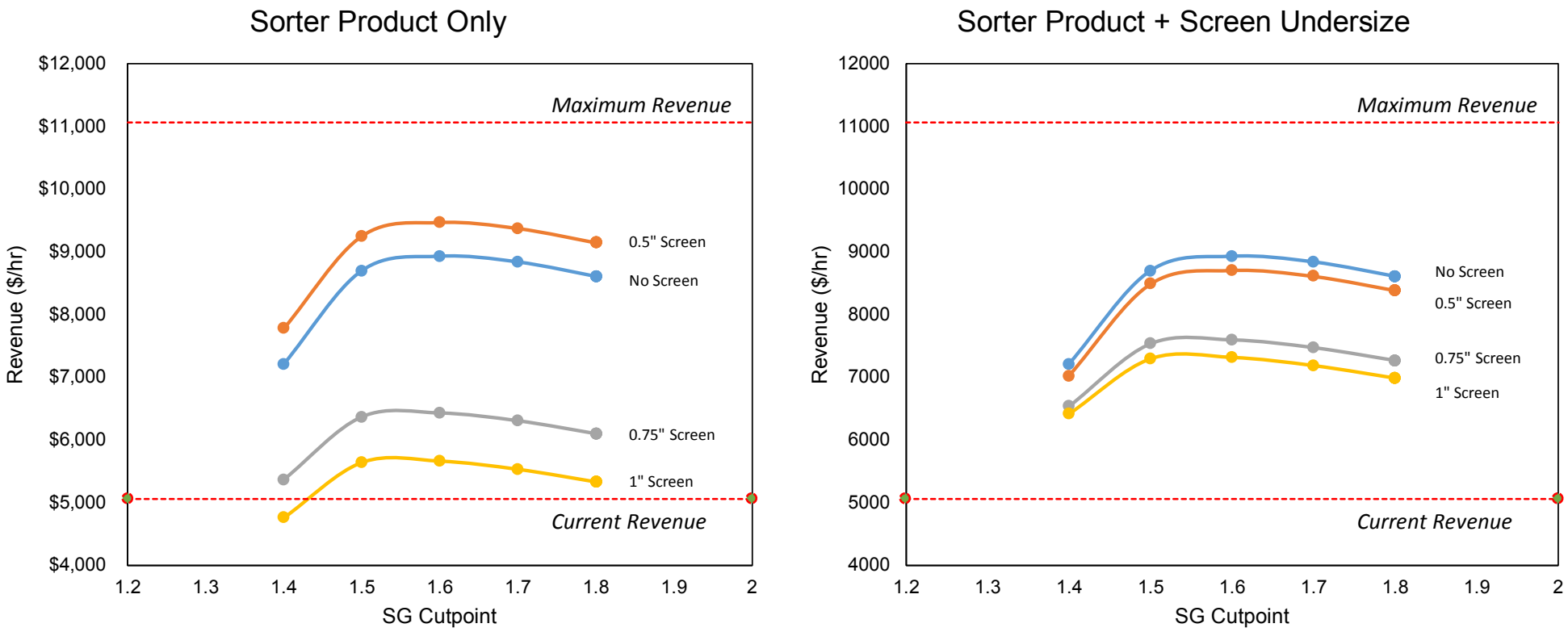
Utility Feedstock Upgrading



- 500 tph ROM coal
- ROM material =40% ash; 9,400 Btu/lb
- Coal Value = $10/ton
- $5,000/hr value
- 6000 hrs/yr operation
- $30 million annual revenue

Parameter	Value
Base Price	$50 / ton
Heat Content Specification	12,500 Btu/lb
Ash Content Specification	12.5%
Heat Adjustment	$0.40 per 100 Btu/lb above or below specification
Ash Adjustment	$1.00 per 1.0% ash above or below specification
Sales Related Costs	$2.50

Revenue Enhancement

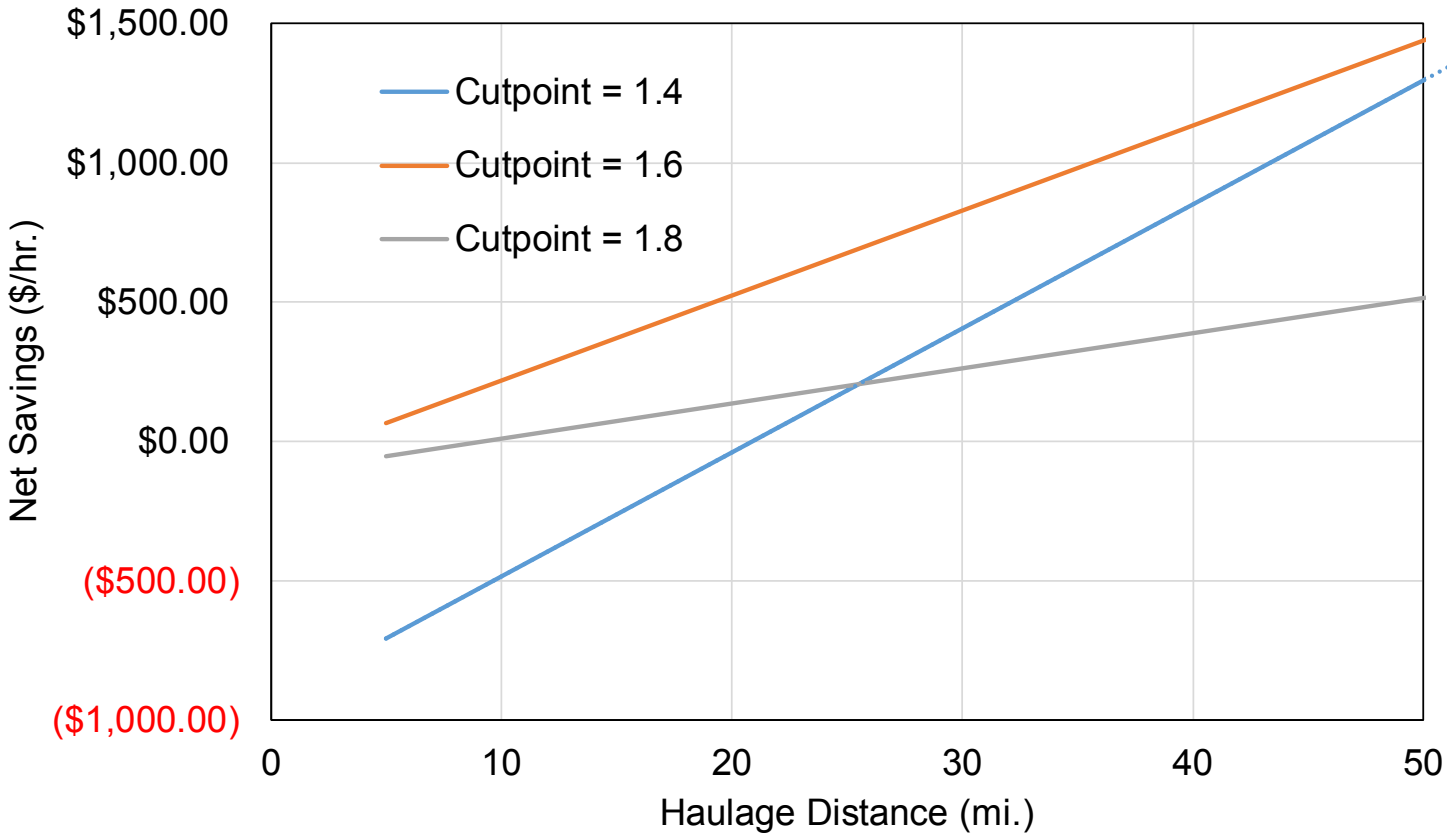


- Revenue Increase to $9500/hr (vs. $5,000/hr) using Sorting only.
- $26 million annual revenue improvement

Source: Dr. Aaron Noble, Virginia Tech (assumed $0.50/ton CAPEX & OPEX)

Application: Mine-to-Plant Transportation Reduction

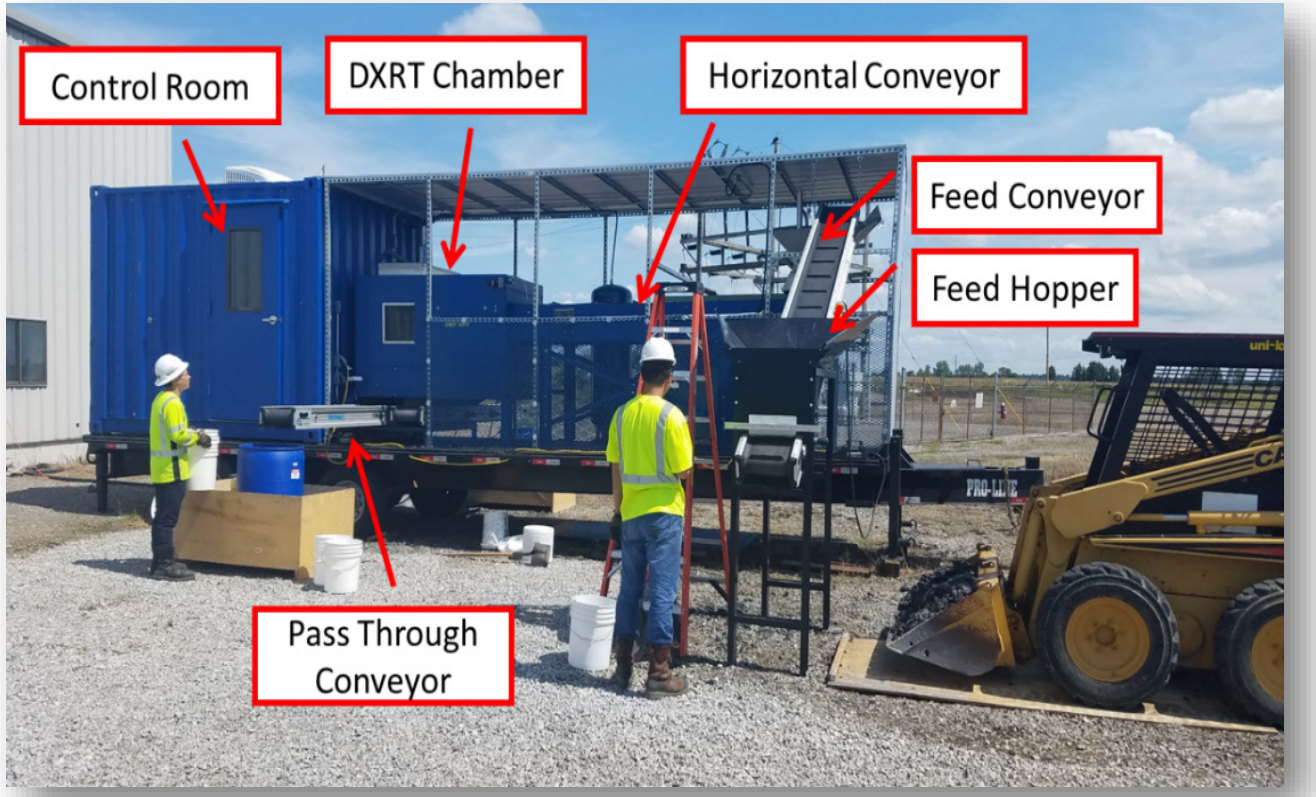
- ROM material contains a significant quantity of liberated rock.
- Operator can reject this material at the mine site to reduce haulage costs.
- Haulage costs were assumed to be fixed at $0.30 per ton-mile.
- Primary output parameter was the net savings between a sorting and no-sorting case.
- Source: Aaron Noble, VT



- 1.6 SG and 1-inch screen provided the superior performance.
- Break even point occurs in less than 5 mile haulage distance.

Conclusions

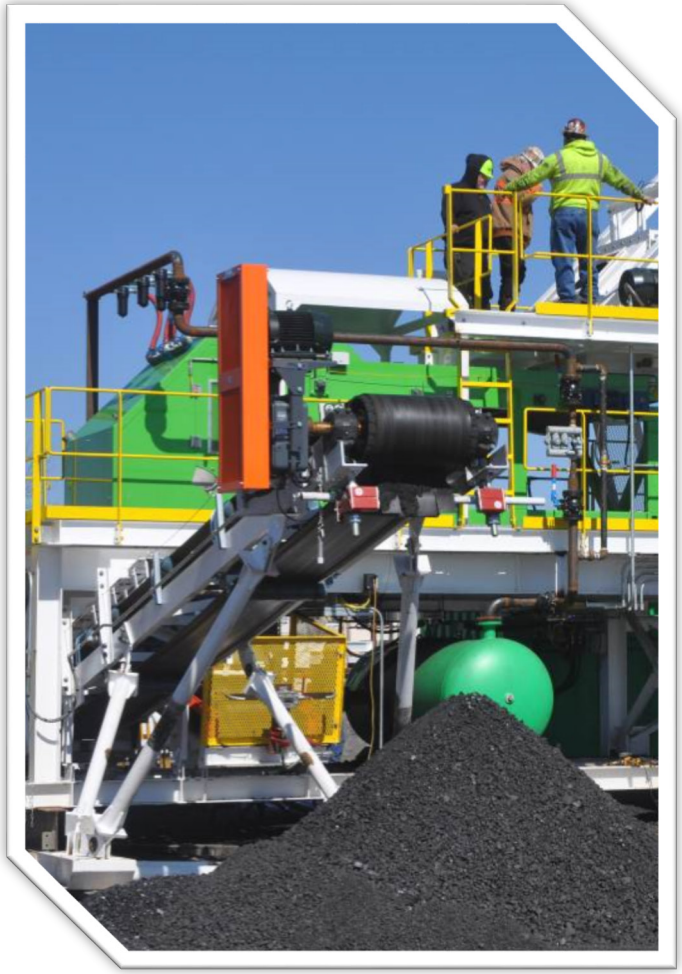
- Efficient separations can be achieved using ore sorting technologies on particles as fine as 6 mm (1/4-inch).
- Fast processing speeds and advancement in sensor technologies have enhanced selectivity and increased throughput capacities.
- Operating costs mainly controlled by the volume of material in the feed that needs to be ejected. Typically in the range of $0.50 to $1.00 per ton.



*MST Unit at the Rare Earth Processing Plant

Conclusions

- Applications include the removal of low grade, valueless rock prior to haulage and direct fuel upgrading for utilities.
- Dual energy XRT sorting provided an excellent separation performance when treating anthracite coal with poor cleanability characteristics.
- Probable error values obtained in our study are similar to those previously reported in publications.



*Mineral Separation Technologies, Inc.

Questions