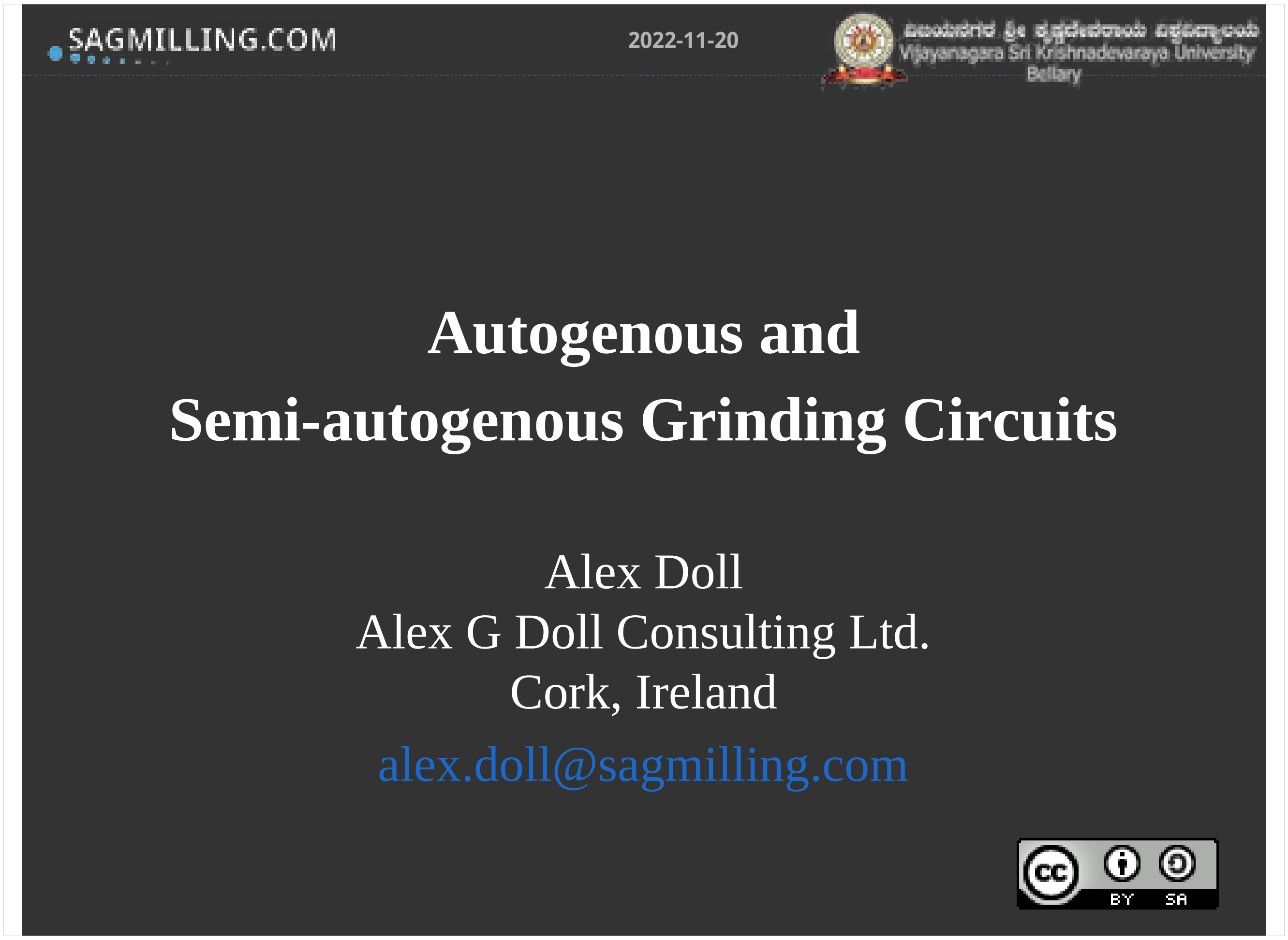


SAGMILLING.COM

2022-11-20

Vijayanagara Sri Krishnadevaraya University
Bellary

Autogenous and Semi-autogenous Grinding Circuits

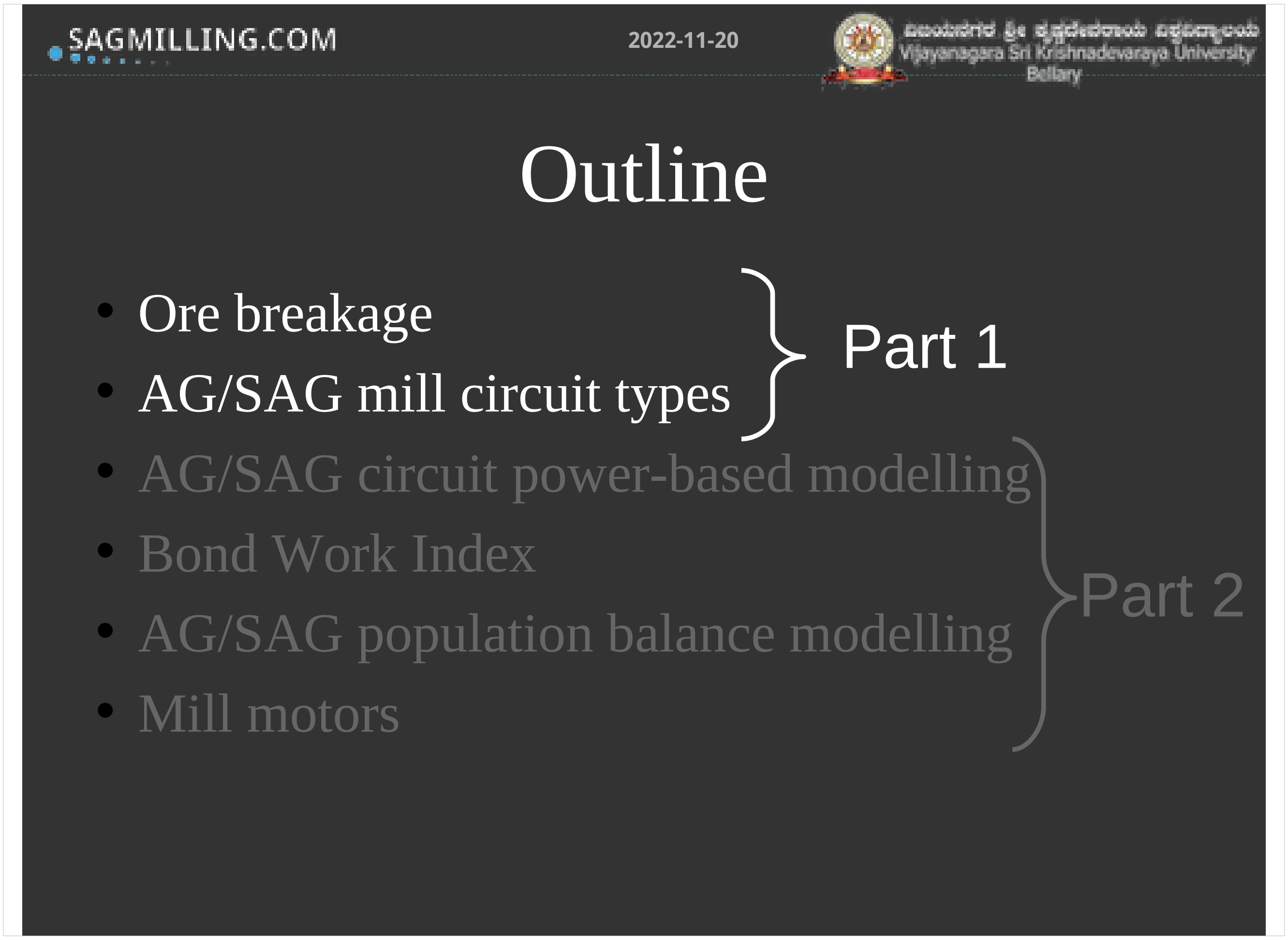
Alex Doll
Alex G Doll Consulting Ltd.
Cork, Ireland
alex.doll@sagmilling.com

Prepared November 20, 2022 for:

Department of Mineral processing
Vijayanagara Sri Krishnadevaraya University Post Graduate centre
Nandihalli, Sandur Karnataka, India

Bio:

Alex Doll is a consulting metallurgical process engineer specializing in power-based comminution modelling and conceptual design. Alex has worked on projects across the Americas, Indonesia, and Australia. He has a BASc in Mining & Mineral Process Engineering (1992) from the University of British Columbia in Vancouver, Canada. Past editor of the Procemin 2012 & 2013 conferences (Santiago, Chile), executive editor of XXVII IMPC in 2014 (Santiago, Chile), and was the Registrar and webmaster for the 2011, 2015, & 2019 SAG Conferences (Vancouver). Alex is a member of industry committees overseeing guidelines for comminution testing & interpretation, and is a Trustee of the SAG Conference Award Foundation, the body that controls the IP of the SAG Conferences held every 4-5 years in Vancouver.



SAGMILLING.COM

2022-11-20

Vijayanagara Sri Krishnadevaraya University
Bellary

Outline

- Ore breakage
- AG/SAG mill circuit types
- AG/SAG circuit power-based modelling
- Bond Work Index
- AG/SAG population balance modelling
- Mill motors

Part 1

Part 2

This presentation is an overview of a lot of topics related to operation and design of autogenous grinding (AG) mills and semiautogenous grinding (SAG) mills. Whole courses can be taught on any of the topics provided here, so the treatment of many topics will be purposely brief.

The intended audience is university students who are in a mineral processing program and have some familiarity with basic concepts like particle size distributions and units operations.

SAGMILLING.COM

2022-11-20

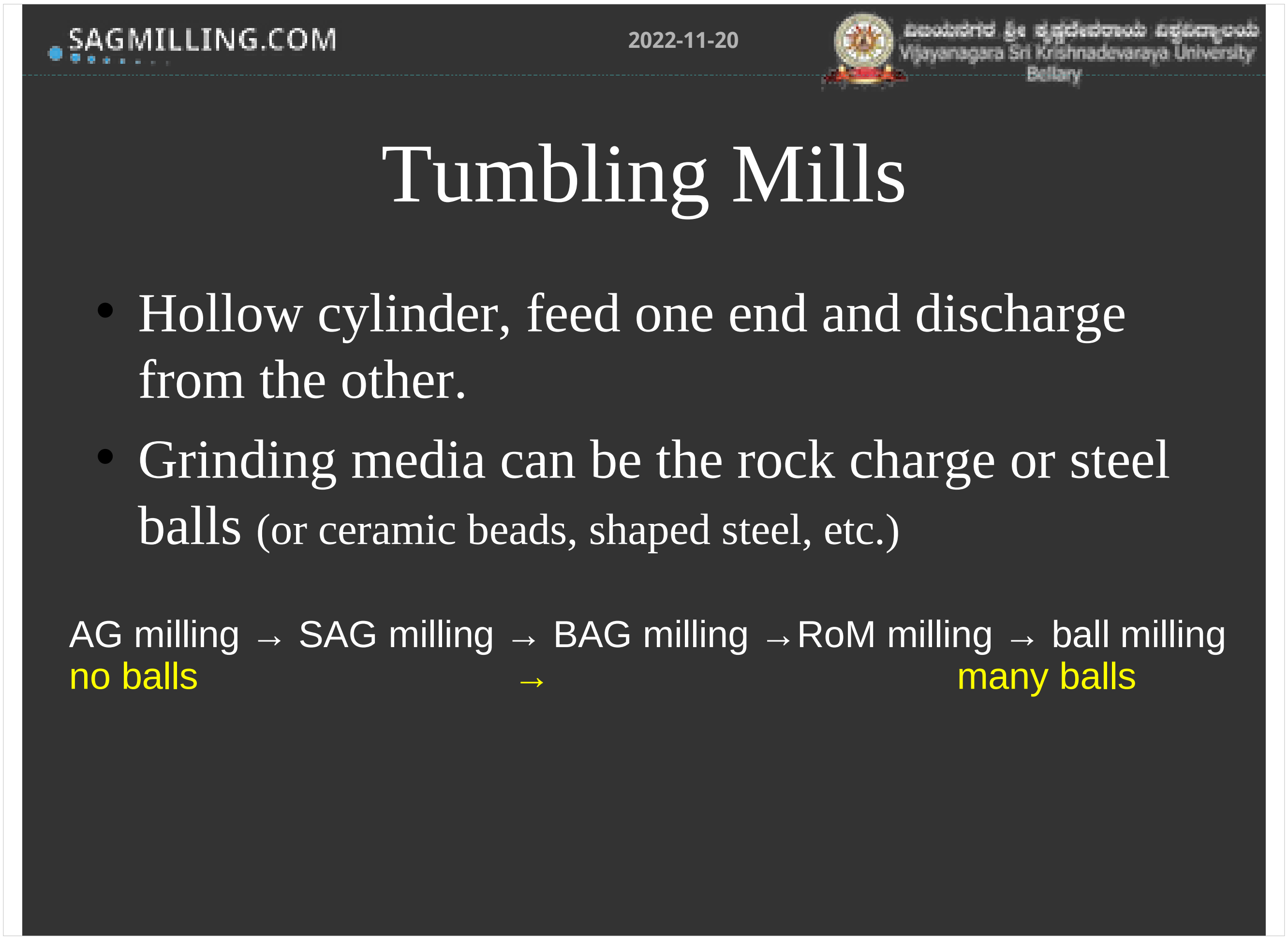
Vijayanagara Sri Krishnadevaraya University
Bellary

Tumbling mills

- Class of equipment that tumble grinding media on ore.
- AG milling uses ore as the media.
- SAG milling includes steel balls.
- Grate discharge.

Most participants in the course will be familiar with tumbling mills, so only the briefest of conceptual reviews will be offered here. Though this section is specific to autogenous and semi-autogenous mills, many of the concepts are general and apply to any form of comminution. There is a continuum where one type of tumbling mill technology bleeds into the next:

Pebble milling is a type of grinding that we won’t be covering; it is a type of secondary autogenous grinding similar to ball milling.



SAGMILLING.COM 2022-11-20

Vijayanagara Sri Krishnadevaraya University Bellary

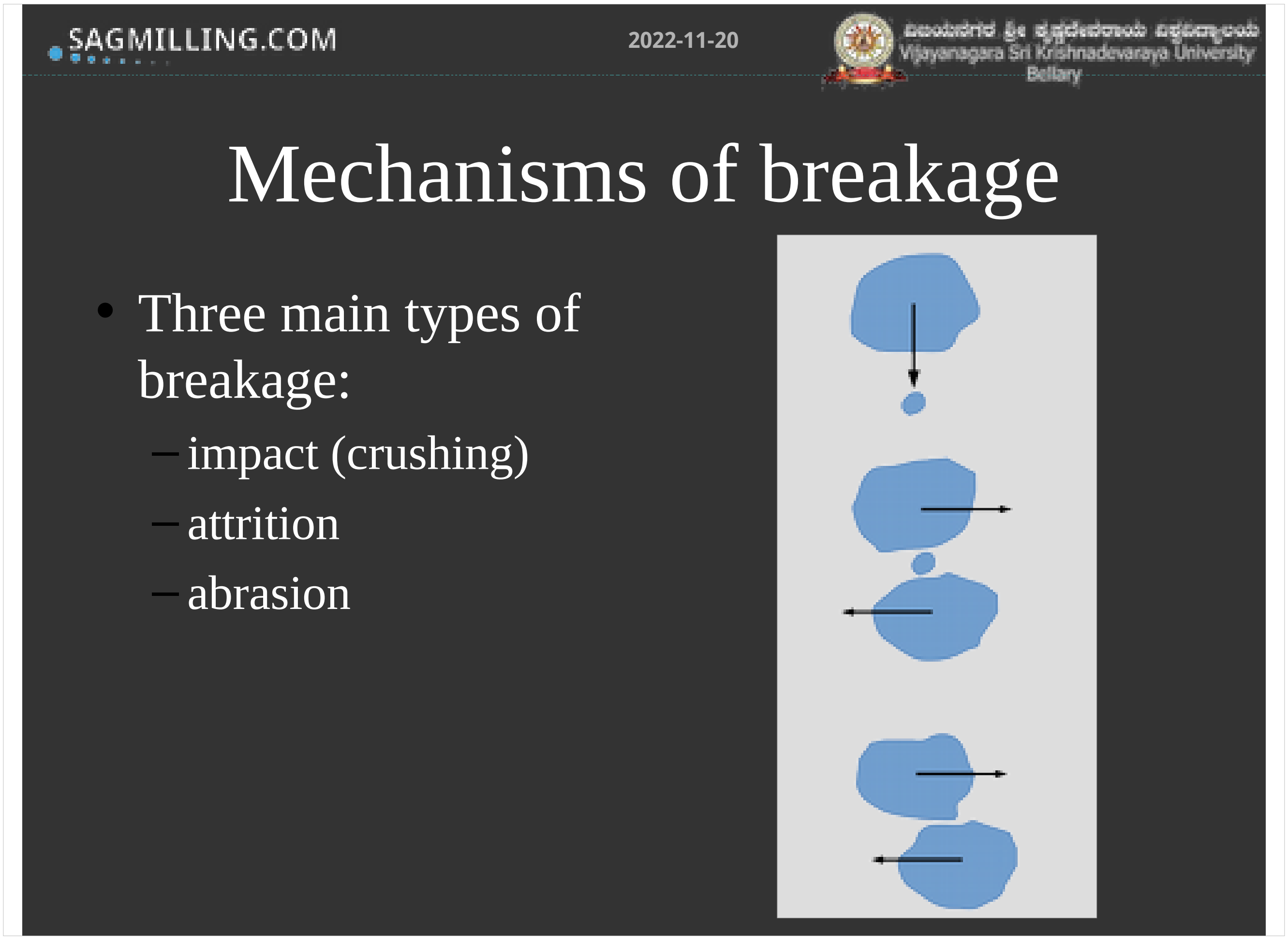
Tumbling Mills

- Hollow cylinder, feed one end and discharge from the other.
- Grinding media can be the rock charge or steel balls (or ceramic beads, shaped steel, etc.)

AG milling → SAG milling → BAG milling →RoM milling → ball milling

no balls → many balls

Tumbling mills started to replace ‘stamp mills’ and ‘querns’ for mineral grinding around the beginning of the 20th century. The various types now represent the majority of mineral grinding equipment used by the Industry.



SAGMILLING.COM 2022-11-20

Vijayanagara Sri Krishnadevaraya University
Bellary

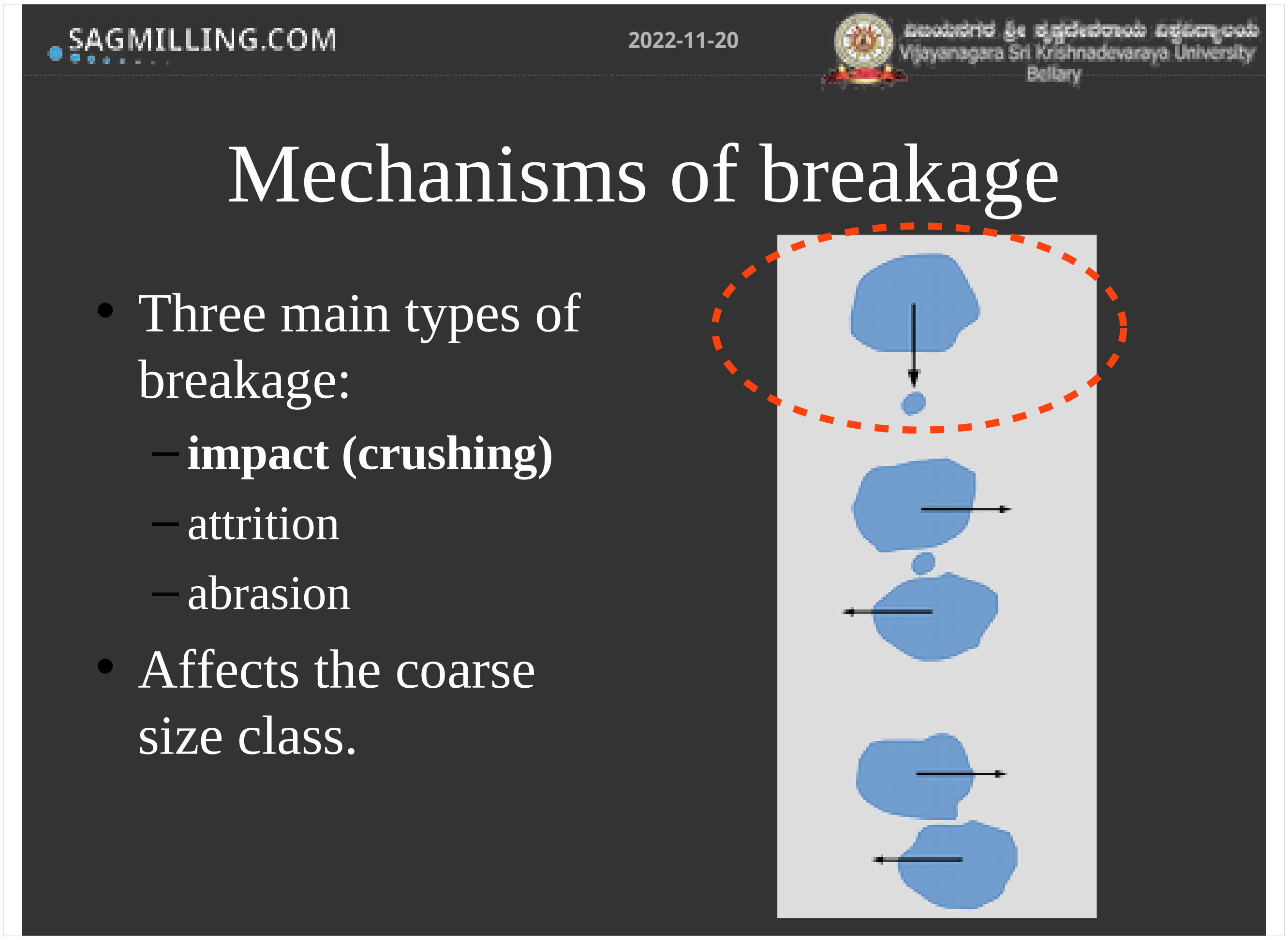
Mechanisms of breakage

- Three main types of breakage:
  - impact (crushing)
  - attrition
  - abrasion

Each mechanism of breakage dominates in a particular size range. Coarse particles tend to break by impact, medium sized particles by attrition, and fine particles are produced by abrasion.

These mechanisms can also go by different names: impact can be described as “self breakage”, attrition as “compression” or “chipping”, and so on.

Key to this discussion is that AG & SAG mills combine all three mechanisms to produce comminution.



SAGMILLING.COM

2022-11-20

Vijayanagara Sri Krishnadevaraya University
Bellary

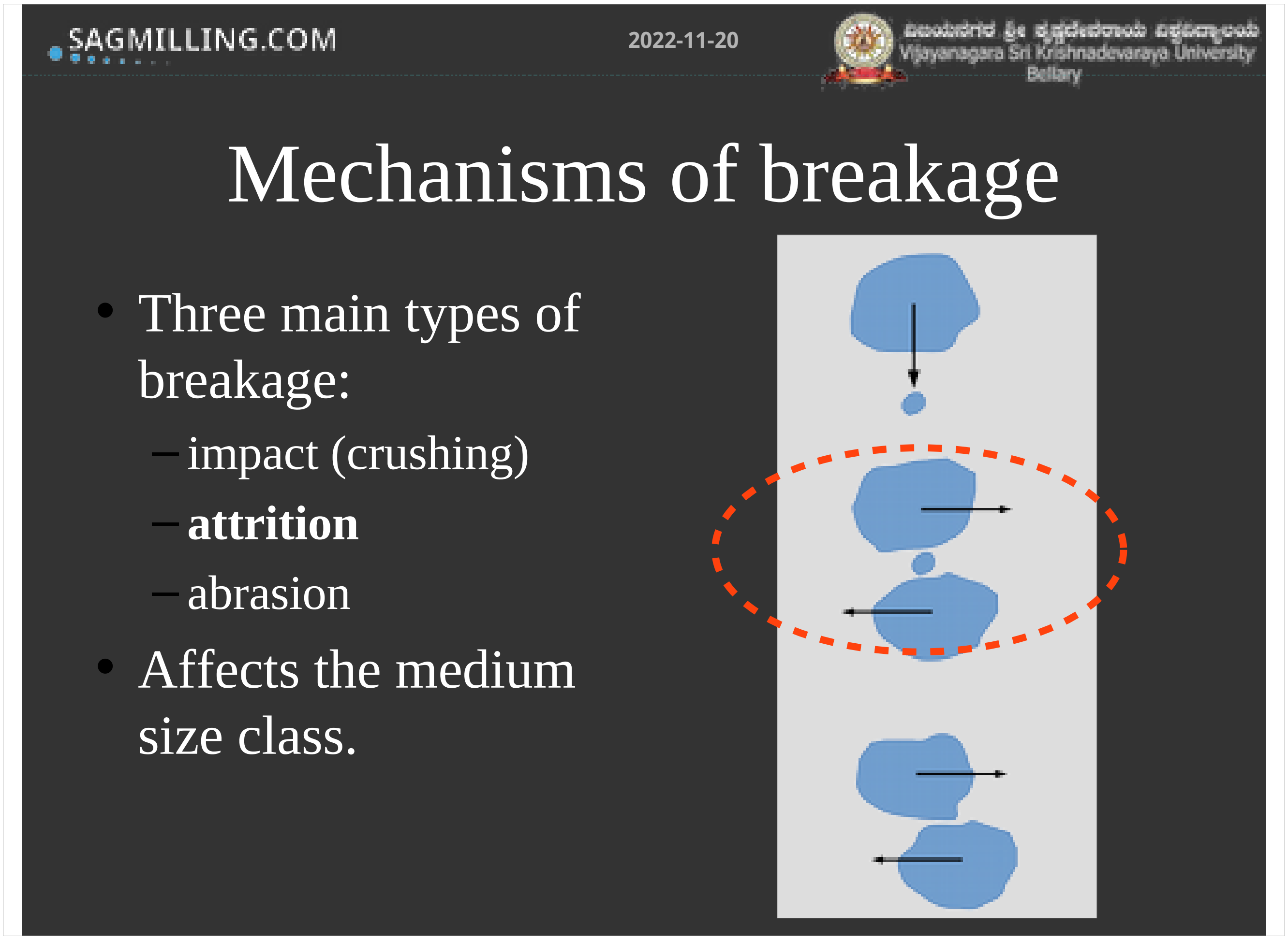
Mechanisms of breakage

- Three main types of breakage:
  - **impact (crushing)**
  - attrition
  - abrasion
- Affects the coarse size class.

Impact or crushing is typically the strongest breakage mechanism in particle sizes above about 30 mm. It tends to be a rapid mechanism causing breakage when a particle is hit by media or the particle impacts either the wall of the mill or the mill charge.

It is strongly influenced by the nature of the grinding media (high-density balls often being more efficient than low-density rocks) and the conditions in the mill's interior (rotation speed, filling level, and lifter design).

A convenient and simple model is to think of impact as creating and exploiting fractures within a particle.



SAGMILLING.COM

2022-11-20

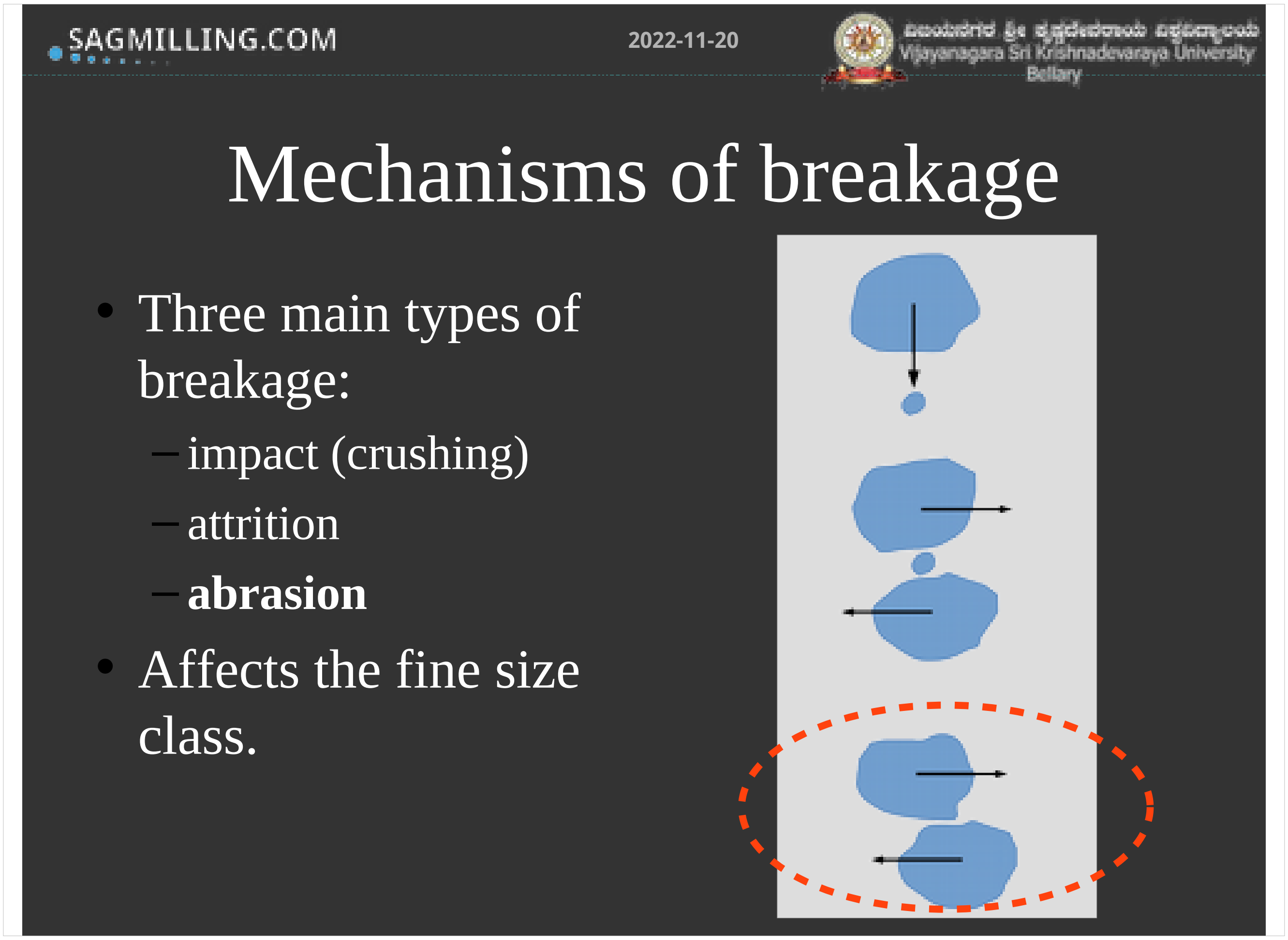
Vijayanagara Sri Krishnadevaraya University
Bellary

Mechanisms of breakage

- Three main types of breakage:
  - impact (crushing)
  - **attrition**
  - abrasion
- Affects the medium size class.

Attrition is usually the dominant breakage mechanism in the size range of 1 mm to 15 mm. This is the type of breakage one expects to see in rod milling, for people familiar with this technology. The charge of the mill is confined and compressed by the weight of charge above, and the motion of the charge causes tangential movement of media that can trap smaller particles, exposing them to high stress that can cause them to shatter or fracture.

A convenient and simple model is to think of attrition as breaking the matrix of a rock where individual grains remain embedded in a coarser structure.



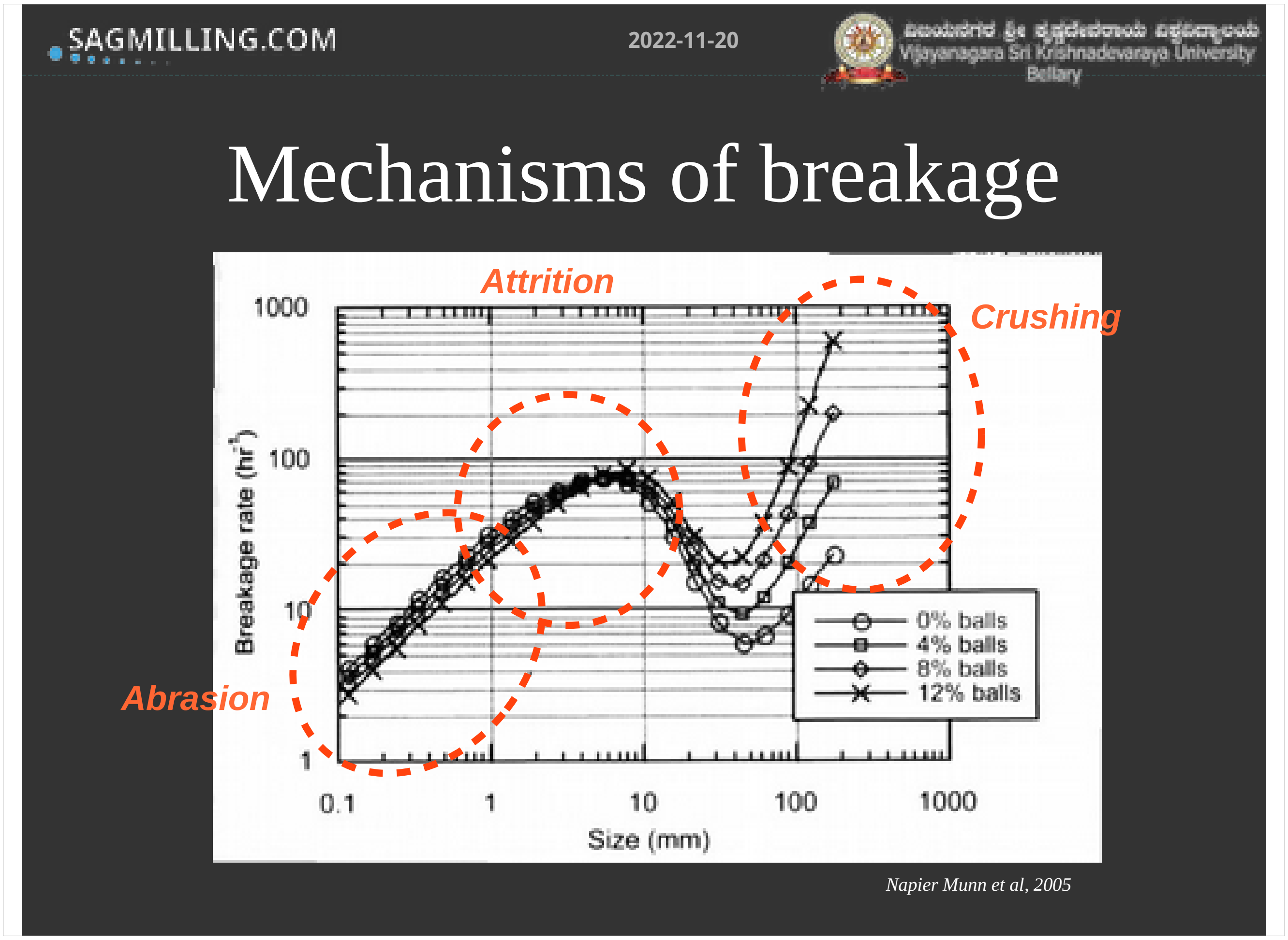
SAGMILLING.COM 2022-11-20 Vijayanagara Sri Krishnadevaraya University Bellary

Mechanisms of breakage

- Three main types of breakage:
  - impact (crushing)
  - attrition
  - **abrasion**
- Affects the fine size class.

Abrasion is usually the dominant breakage mechanism in the size range below 1 mm. It is caused by surficial scraping of particles passing tangentially under compression. Product sizes tend to be bimodal; the original coarse particles are still coarse but a small amount of fines are liberated from their surfaces.

A convenient and simple model is to think of abrasion as the mechanism where an individual grain is liberated from the matrix of a rock.



SAGMILLING.COM

2022-11-20

Vijayanagara Sri Krishnadevaraya University
Bellary

Mechanisms of breakage

Napier Munn et al, 2005

This is a “breakage rate” curve that shows the frequency at which a particle breaks (y-axis) as a function of the particle size (x-axis). The higher the breakage rate, the more likely that particle is to break in a particular time interval.

The diagram is a generalized curve for AG and SAG milling where we can see the mill is more efficient at breaking the 8 mm and 200 mm sized particle.

There is a noticeable dip around 40 mm. This is a gap where neither attrition nor crushing is particular effective. This is known as the “critical size” that creates pebbles.

SAGMILLING.COM

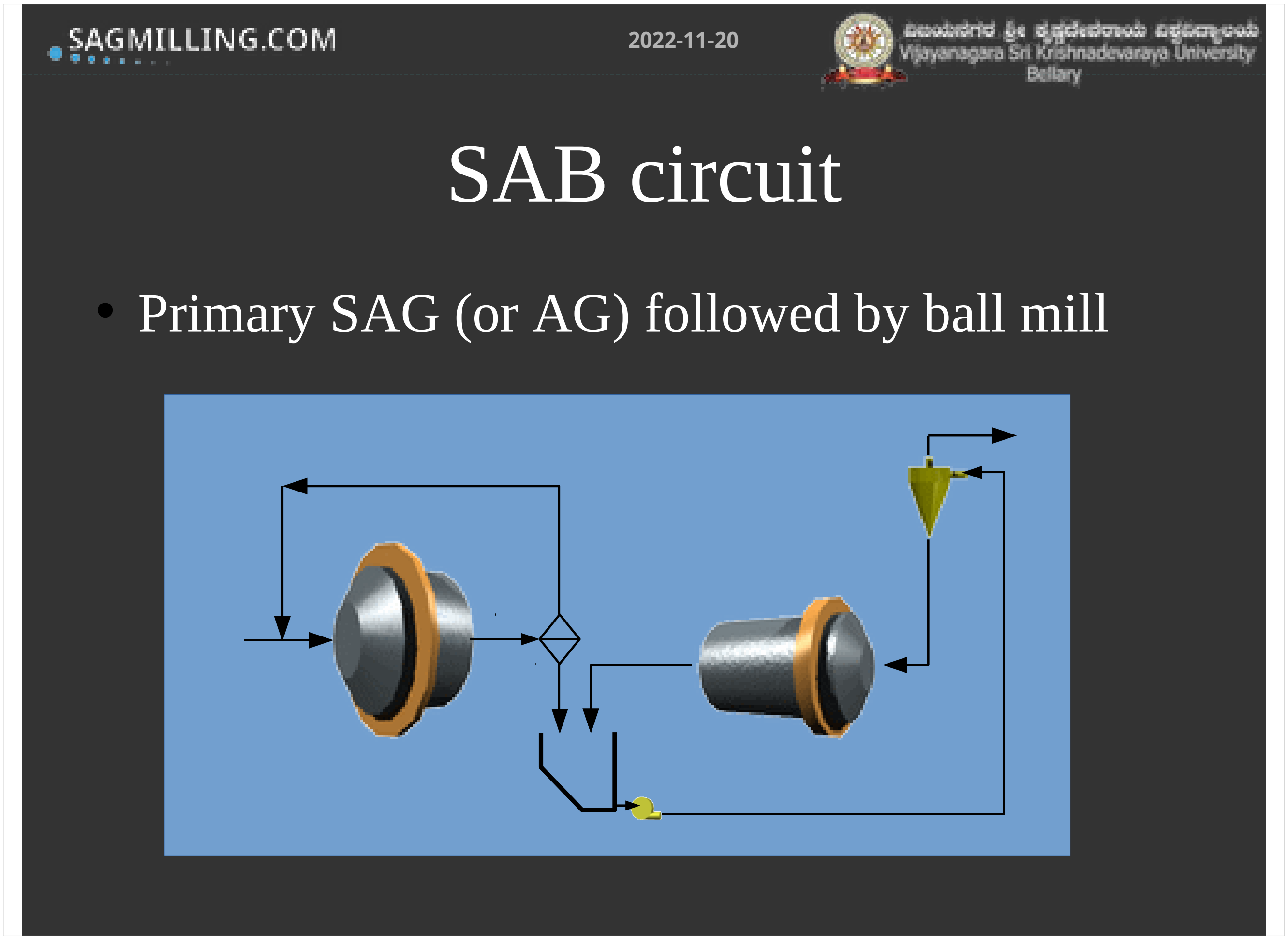
2022-11-20

ವಿಜಯನಗರ ಶ್ರೀ ಕೃಷ್ಣದೇವರಾಯ ವಿಶ್ವವಿದ್ಯಾಲಯ
Vijayanagara Sri Krishnadevaraya University
Bellary

Milling circuits

The different mechanisms of breakage are also employed differently in the various types of milling equipment. Ball mills tend to produce a lot of attrition and abrasion but little impact. SAG mills can produce a lot of impact if operated with a high ball charge and low filling. Rod and AG mills can produce a lot of attrition and varying amounts of impact and abrasion.

Arraying different mills can take advantage of the strengths of particular equipment.



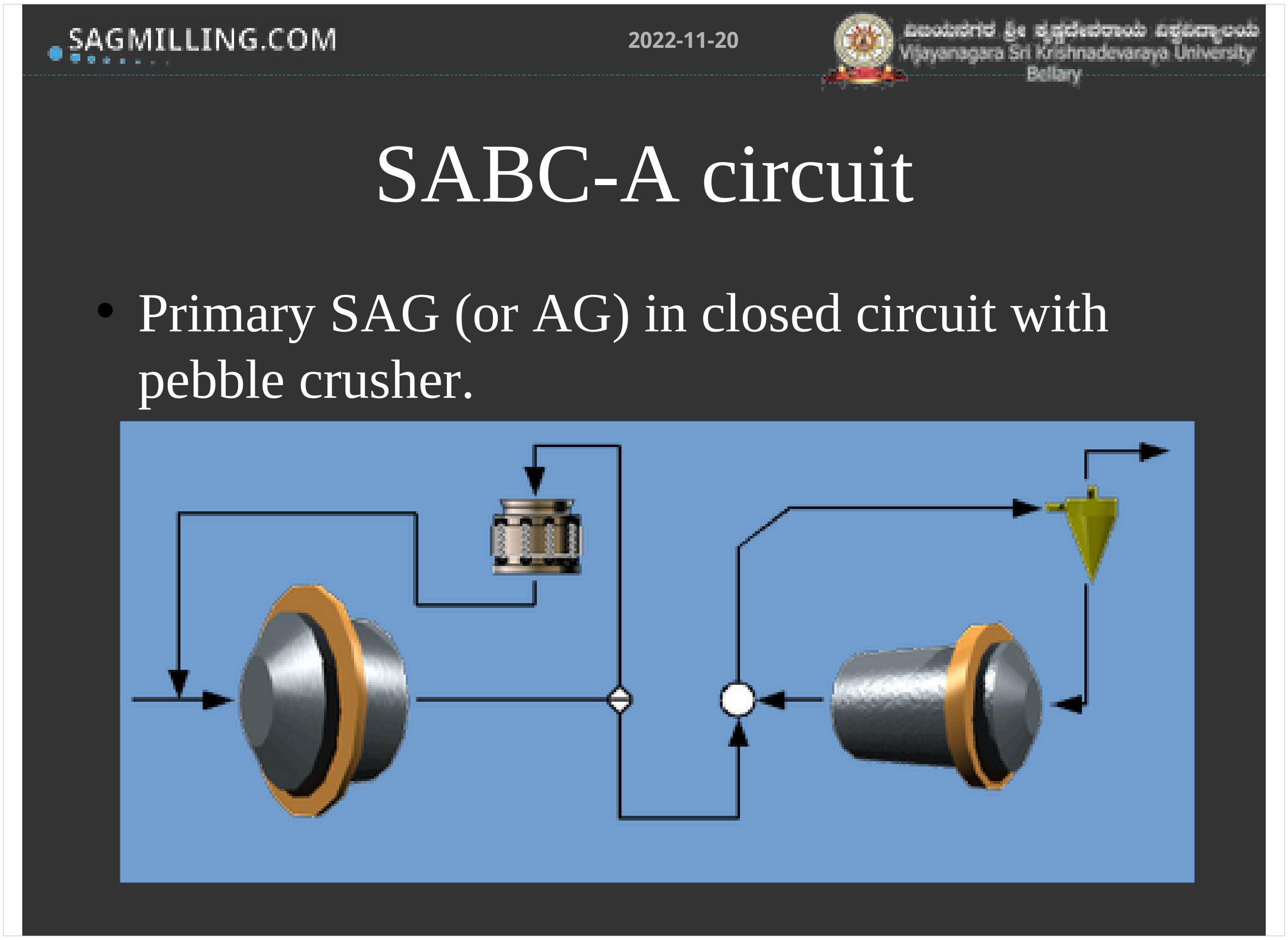
SAGMILLING.COM 2022-11-20 Vijayanagara Sri Krishnadevaraya University Bellary

SAB circuit

- Primary SAG (or AG) followed by ball mill

This is the most basic type of SAG or AG circuit where the primary crushed ore enters the SAG or AG mill, gets ground to a "transfer size" where it exits the mill and is then passed to the closed circuit ball mill circuit. The SAG/AG mill product will usually contain a lot of finished product size, so it is useful to put the the SAG/AG product in the pumpbox that feeds the hydrocyclone (as opposed to putting it directly into the ball mill feed).

Pebbles can either be held inside the mill by adjusting the grates to a fine size, or can be ejected from the mill, separated by a coarse screen and then re-fed into the mill feed. The pebbles will then pass down the length of the mill and (hopefully) be crushed.



SAGMILLING.COM

2022-11-20

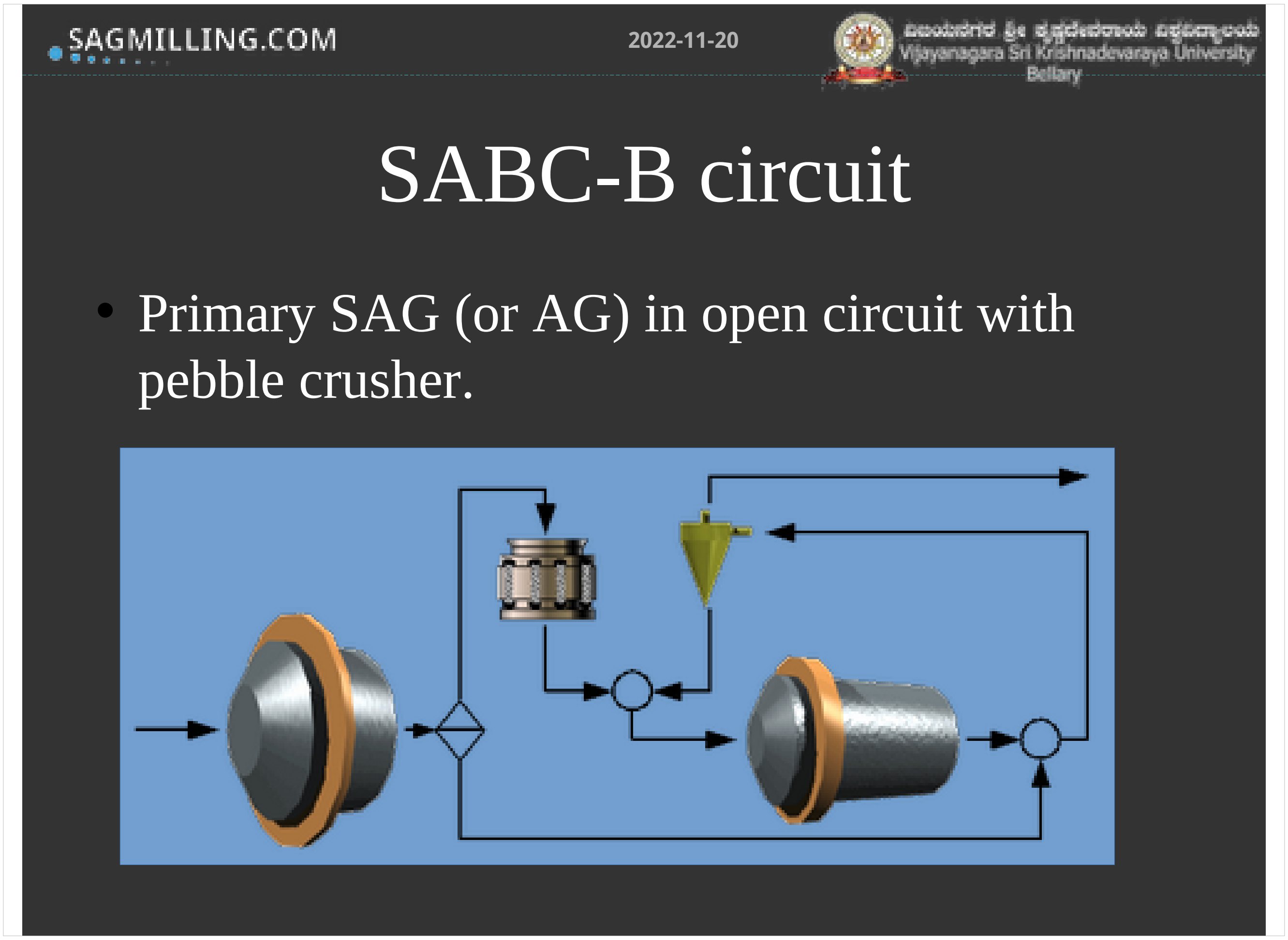
Vijayanagara Sri Krishnadevaraya University
Bellary

SABC-A circuit

- Primary SAG (or AG) in closed circuit with pebble crusher.

AG and SAG mills are very efficient at making angular particles round. Crushers are very efficient at making round particles angular. So there is a potential synergy from passing hard, rounded pebbles from a AG or SAG mill to a dedicated pebble crusher. The crusher product returns to the AG/SAG mill for further grinding.

Grinding steel must not be allowed into the pebble crusher! Sophisticated steel removing magnet system and metal detection are used to protect pebble crushers from grinding media. This is a problem if you have a magnetic ore – the metal detectors can't distinguish between magnetic ore that should be crushed and grinding media that shouldn't.



SAGMILLING.COM

2022-11-20

Vijayanagara Sri Krishnadevaraya University
Bellary

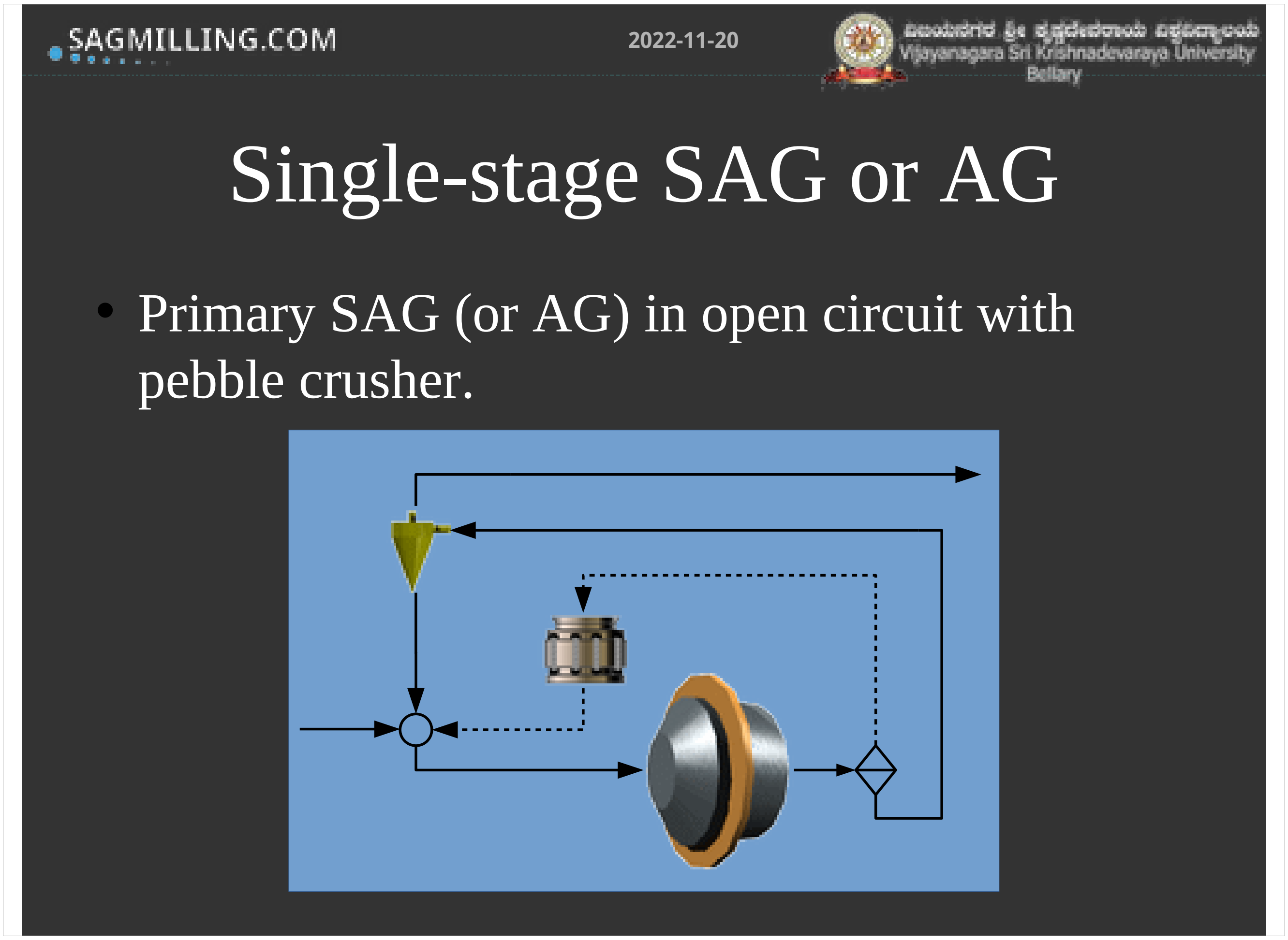
SABC-B circuit

- Primary SAG (or AG) in open circuit with pebble crusher.

This pebble crushing arrangement sends crushed pebbles to the ball mill feed instead of the AG/SAG mill. It boosts the throughput of the AG/SAG mill (because there is no recycle), but loads the ball mills instead. Often an existing plant that observes their SAG mill is limiting throughput, but the ball mills are under-loaded can open-circuit the primary mill to better balance the grinding load with the secondary mill.

The coarse transfer size to the ball mill makes this circuit unsuitable for most fine-grinding applications such as gold ores with 100 µm P_{80} targets. It is mostly employed in huge porphyry copper mines with >100 kt/d throughput with coarse P_{80} targets.

Another variation is SABC-AB where a gate (chute) can toggle crushed pebbles to either the primary or secondary mill.



SAGMILLING.COM

2022-11-20

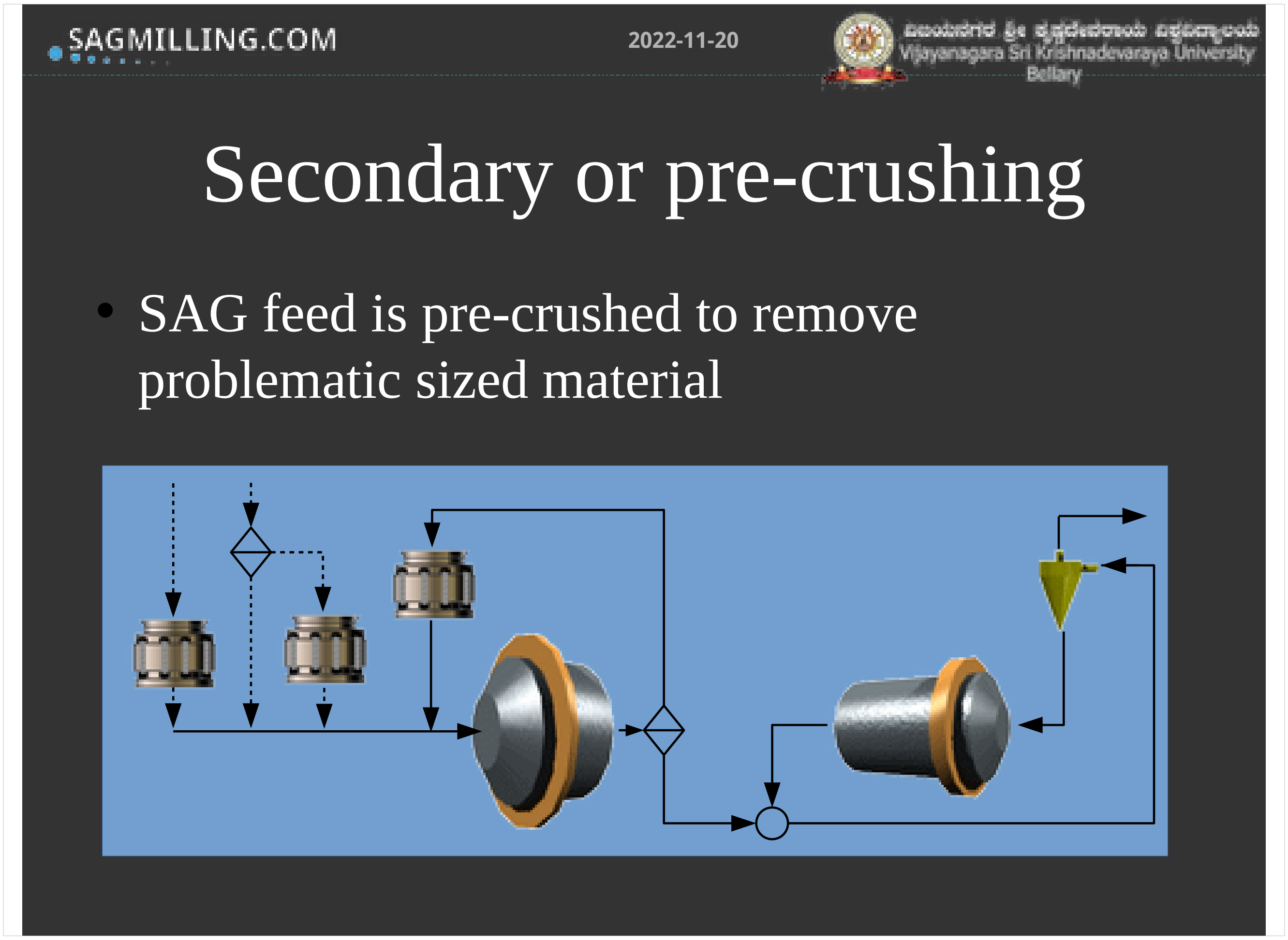
Vijayanagara Sri Krishnadevaraya University
Bellary

Single-stage SAG or AG

- Primary SAG (or AG) in open circuit with pebble crusher.

A simple and cost-effective circuit for a small mill that requires a fine grind is a single-stage SAG or AG mill (no secondary ball mill). The mill is closed with a hydrocyclone (just as a ball mill would be) and may include a pebble recirculation and/or crushing system. These tend to be inefficient, but the simplicity makes them desirable for small operations (and cheap, too!). Many examples of this circuit exist in Western Australia.

The abrasion component of breakage is important here because the mill must produce the final product size.



SAGMILLING.COM

2022-11-20

Vijayanagara Sri Krishnadevaraya University
Bellary

Secondary or pre-crushing

- SAG feed is pre-crushed to remove problematic sized material

Secondary crushing or screening and partial pre-crushing of SAG feed is becoming more common. Secondary crushing is a debottlenecking strategy to boost the amount of breakage ahead of the primary grinding mills. They are typically used in situations where increasing throughput is desired, but there is no unused power in either the primary or secondary grinding circuit.

Pre-crushing and secondary crushing has all the problems associated with multi-stage crushing plants (capital costs, dust) and will eliminate the coarse material that provides the autogenous crushing component (no big rocks that can fall on smaller rocks). Care must be taken to avoid feeding pebble-sized material to the primary mill!

SAGMILLING.COM

2022-11-20

ವಿಜಯನಗರ ಶ್ರೀ ಕೃಷ್ಣದೇವರಾಯ ವಿಶ್ವವಿದ್ಯಾಲಯ
Vijayanagara Sri Krishnadevaraya University
Bellary

Forwards or backwards?

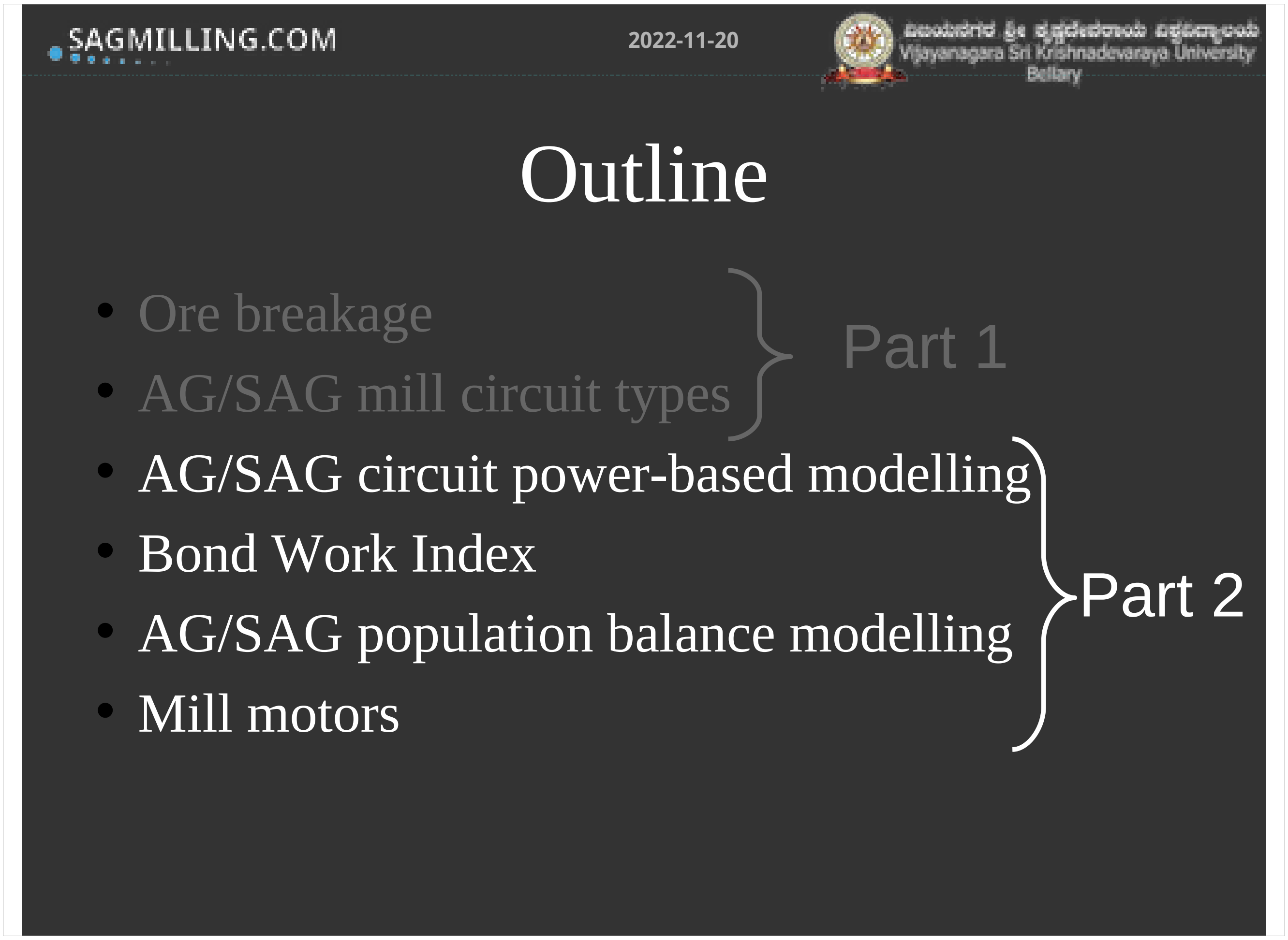
- The industry moved away from multi-stage crushing to AG/SAG milling
- Is the industry moving back to multi-stage crushing?

The History of Grinding
Alban J. Lynch
Chester A. Rowland
SME

The Canadian mining industry embraced AG and SAG milling in the 1970’s/80’s because it solved a lot of problems that existed with with multi-stage crushing plants that were needed ahead of single-stage ball mills. These include:

- freezing fine ore bins,
- the need to heat conveyor galleries in winter, and
- dust created in crushing and conveyor transfers (OH&S)

People who focus on the “energy savings” of HPGR and other crushing equipment must consider the energy required for conveying, heating a larger building footprint, dust collection and the larger ball mills. There are ores better suited to HPGR than to AG/SAG milling, but they tend to be limited to the hardest ores.



SAGMILLING.COM 2022-11-20

Vijayanagara Sri Krishnadevaraya University
Bellary

Outline

- Ore breakage
- AG/SAG mill circuit types

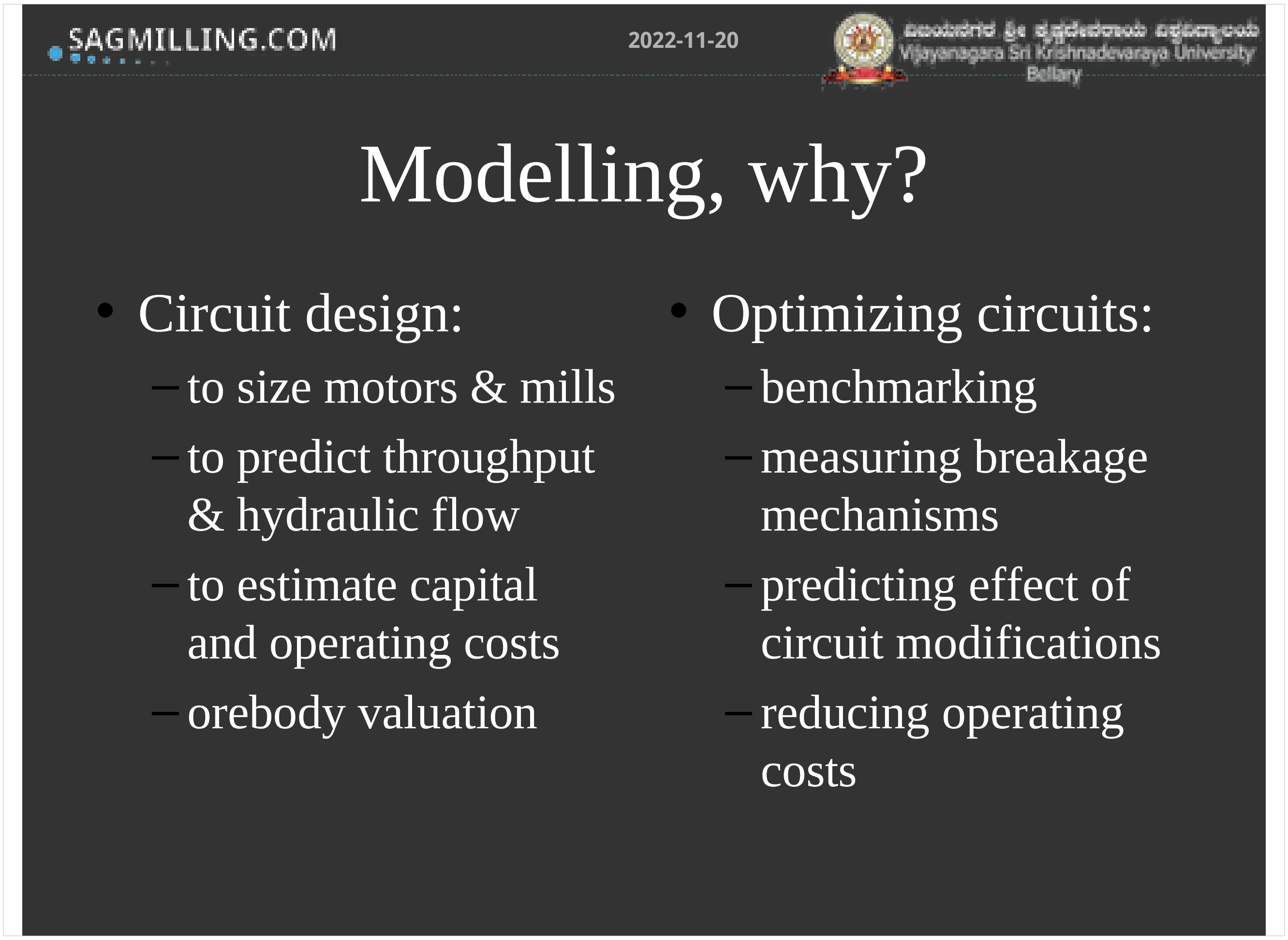
Part 1

- AG/SAG circuit power-based modelling
- Bond Work Index
- AG/SAG population balance modelling
- Mill motors

Part 2

This presentation is an overview of a lot of topics related to operation and design of autogenous grinding (AG) mills and semiautogenous grinding (SAG) mills. Whole courses can be taught on any of the topics provided here, so the treatment of many topics will be purposely brief.

The intended audience is university students who are in a mineral processing program and have some familiarity with basic concepts like particle size distributions and units operations.



SAGMILLING.COM 2022-11-20 Vijayanagara Sri Krishnadevaraya University Bellary

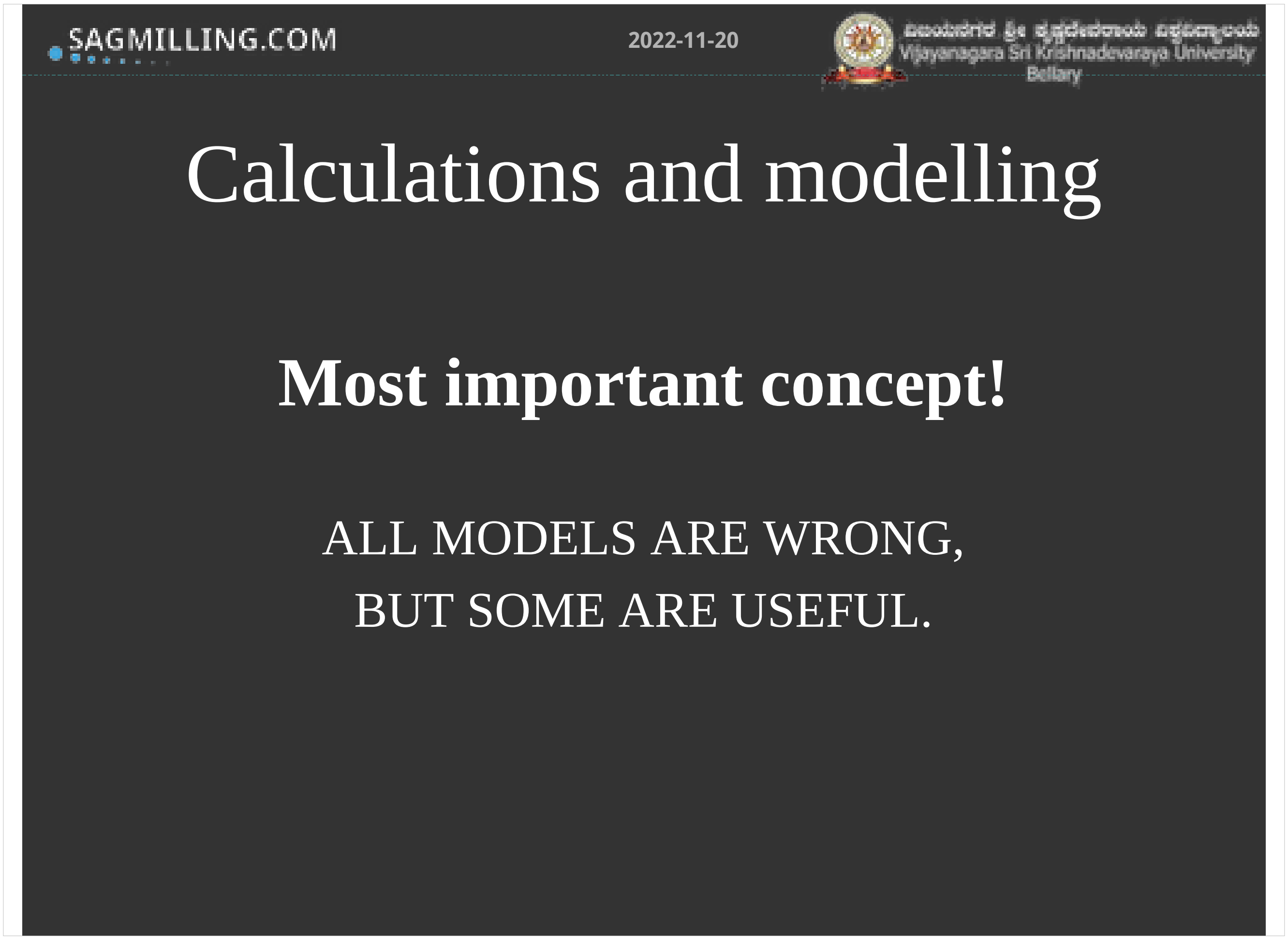
Modelling, why?

- Circuit design:
  - to size motors & mills
  - to predict throughput & hydraulic flow
  - to estimate capital and operating costs
  - orebody valuation
- Optimizing circuits:
  - benchmarking
  - measuring breakage mechanisms
  - predicting effect of circuit modifications
  - reducing operating costs

Modelling is used in circuit design and optimizing, but is a discussion of modelling necessary if all you want to do is “run a mill”? Short answer is “yes if you want to run a mill well”.

Modelling provides a frame-work that you can use to understand what your mill might be doing and what it should perhaps be doing. If nothing else, you can use the mathematical models as a score-card to judge how well your mill is operating.

Many of the concepts of modelling include concepts like “shell power” that are useful when communicating to people who are not familiar with your particular mill. When talking to a consultant, for example, your DCS power display is somewhat unintelligible without a conversion between your DCS and the mill shell power.



SAGMILLING.COM

2022-11-20

Vijayanagara Sri Krishnadevaraya University
Bellary

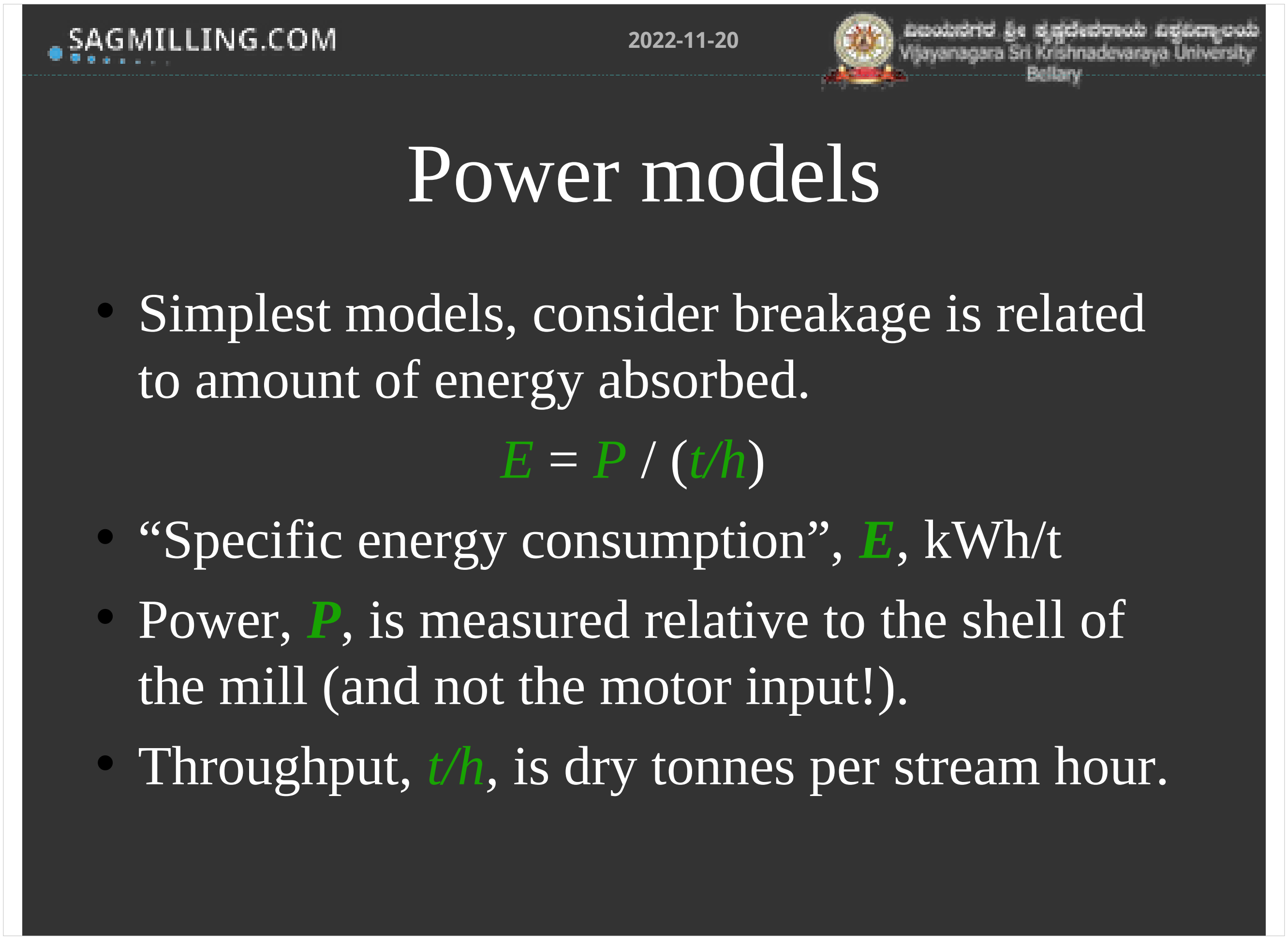
Calculations and modelling

Most important concept!

ALL MODELS ARE WRONG,
BUT SOME ARE USEFUL.

The models “should” lead to the same answers. However, the real world doesn't always work as models predict, and you'll see that different models can give somewhat greater or lesser results. Different models are built from different backgrounds, and it is possible that one of them might be better suited to your needs than another.

Another thought: If you are designing the financial model of a project, then you may want to use a model that gives you conservative (lower) throughput estimates. If you are designing the pumps and pipes for a grinding circuit, then you may want to use conservative (higher) throughput estimates. The definition of what is “conservative” will change depending what you are doing, and the choice of model might also change.



SAGMILLING.COM

2022-11-20

Vijayanagara Sri Krishnadevaraya University
Bellary

Power models

- Simplest models, consider breakage is related to amount of energy absorbed.

$$E = P / (t/h)$$

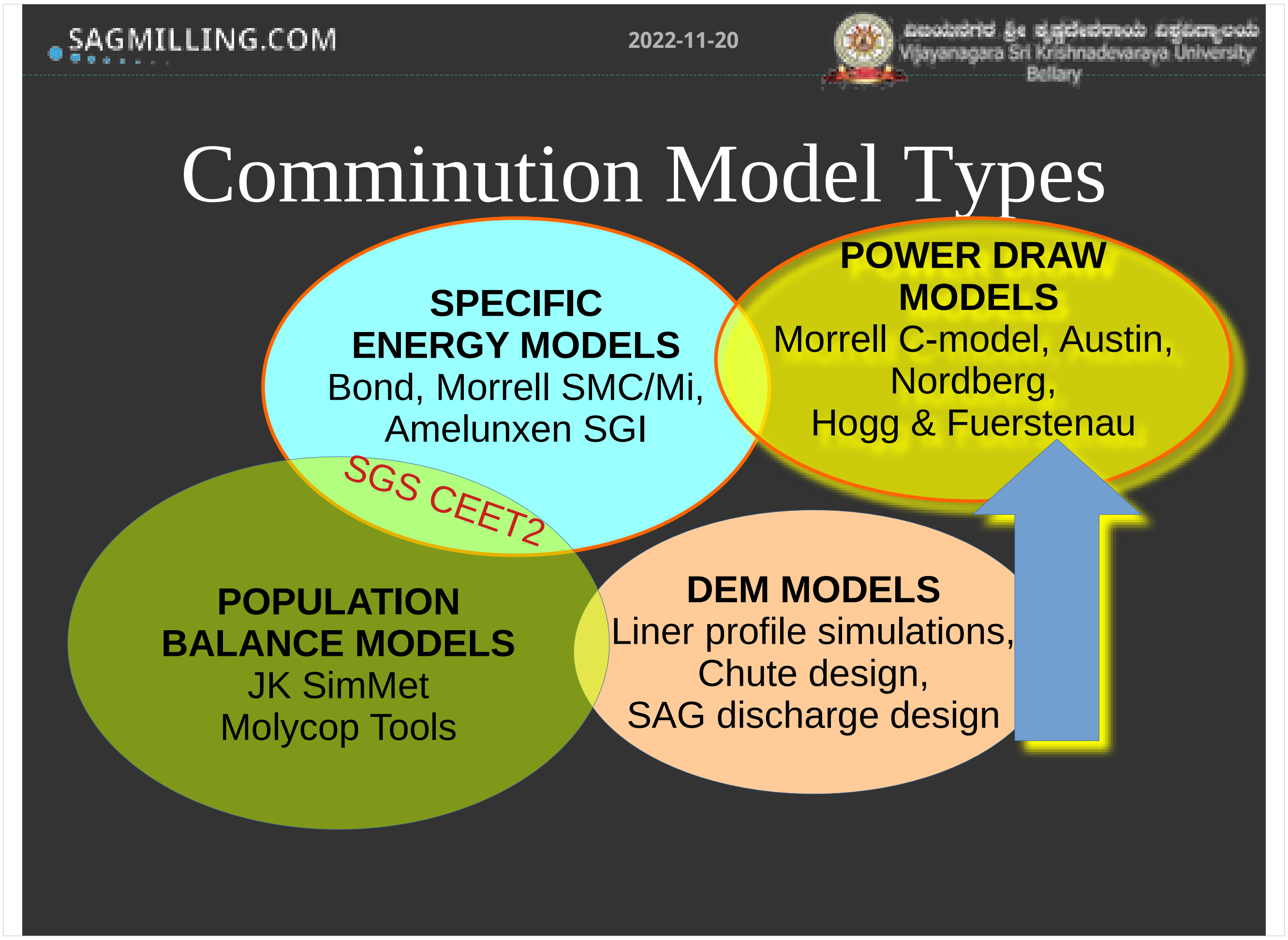
- "Specific energy consumption", **E**, kWh/t
- Power, **P**, is measured relative to the shell of the mill (and not the motor input!).
- Throughput, t/h, is dry tonnes per stream hour.

This class of model is the most widely used for design and is also suitable for benchmarking prior to a mill optimization program.

A variety of empirical models exist to associate laboratory testing to industrial-scale grindability, E. Once E is determined then the equations can be run either of to ways:

1. Predict the power, P, required to achieve a desired throughput, t/h. This is a typical design situation.

2. Predict the throughput, t/h, possible given a mill power, P. This is a typical benchmarking or optimization for an existing mill. If the mill achieves or exceeds the benchmark, then there may be minimal opportunity to improve it further.



SAGMILLING.COM

2022-11-20

Vijayanagara Sri Krishnadevaraya University
Bellary

Comminution Model Types

SPECIFIC ENERGY MODELS
Bond, Morrell SMC/Mi,
Amelunxen SGI

POWER DRAW MODELS
Morrell C-model, Austin,
Nordberg,
Hogg & Fuerstenau

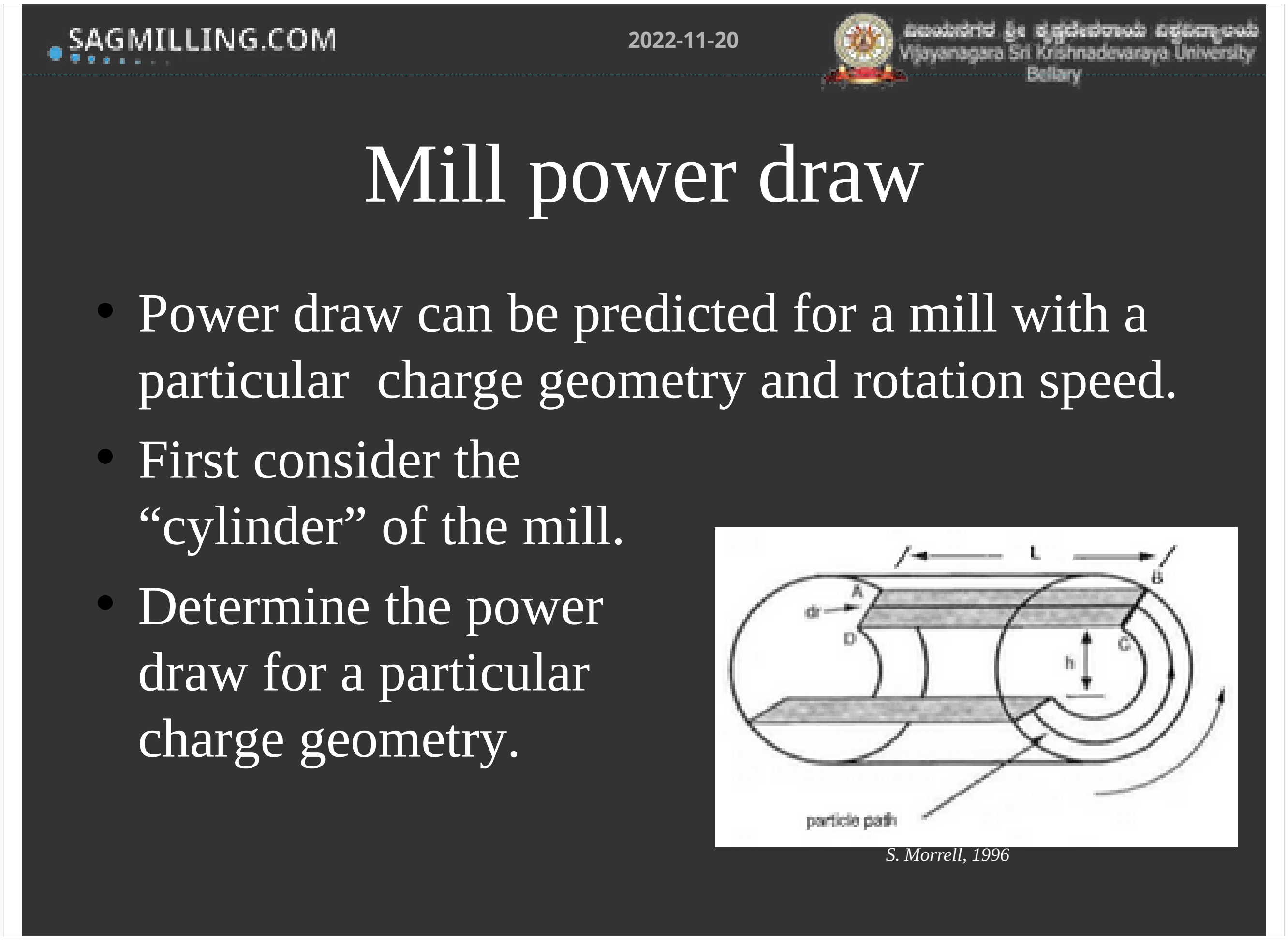
SGS CEET2

POPULATION BALANCE MODELS
JK SimMet
Molycop Tools

DEM MODELS
Liner profile simulations,
Chute design,
SAG discharge design

Modelling of comminution systems can usually be classified into four categories:

- **Power draw models.** Predicts how much power will be drawn by a mill of a specified geometry with a particular charge geometry & density.
- **Specific Energy models.** These assume 'standard' particle size distributions and require only a single size point (usually 80% passing) to characterise an entire particle size distribution. Simple and mostly linear models, they can be run very quickly using computers.
- **Population balance models.** These track flows of individual size classes separately and operate well in situations where "non-standard" particle size distributions are being used. Models tend to have a large number of configuration parameters that make them suitable for optimisation of an existing mill, but provide too many degrees of freedom for early design work.
- **Descrete element models (DEM).** These use fundamental physics to model the motion of simulated particles in a gravity field, and use complex collision calculations to predict the motion of particles as they move within, for example, a turning mill. More complex calculations than other models, these are suited only to detailed design of components of a milling system, such as the lifter face angle and height.



SAGMILLING.COM

2022-11-20

Vijayanagara Sri Krishnadevaraya University
Bellary

Mill power draw

- Power draw can be predicted for a mill with a particular charge geometry and rotation speed.
- First consider the "cylinder" of the mill.
- Determine the power draw for a particular charge geometry.

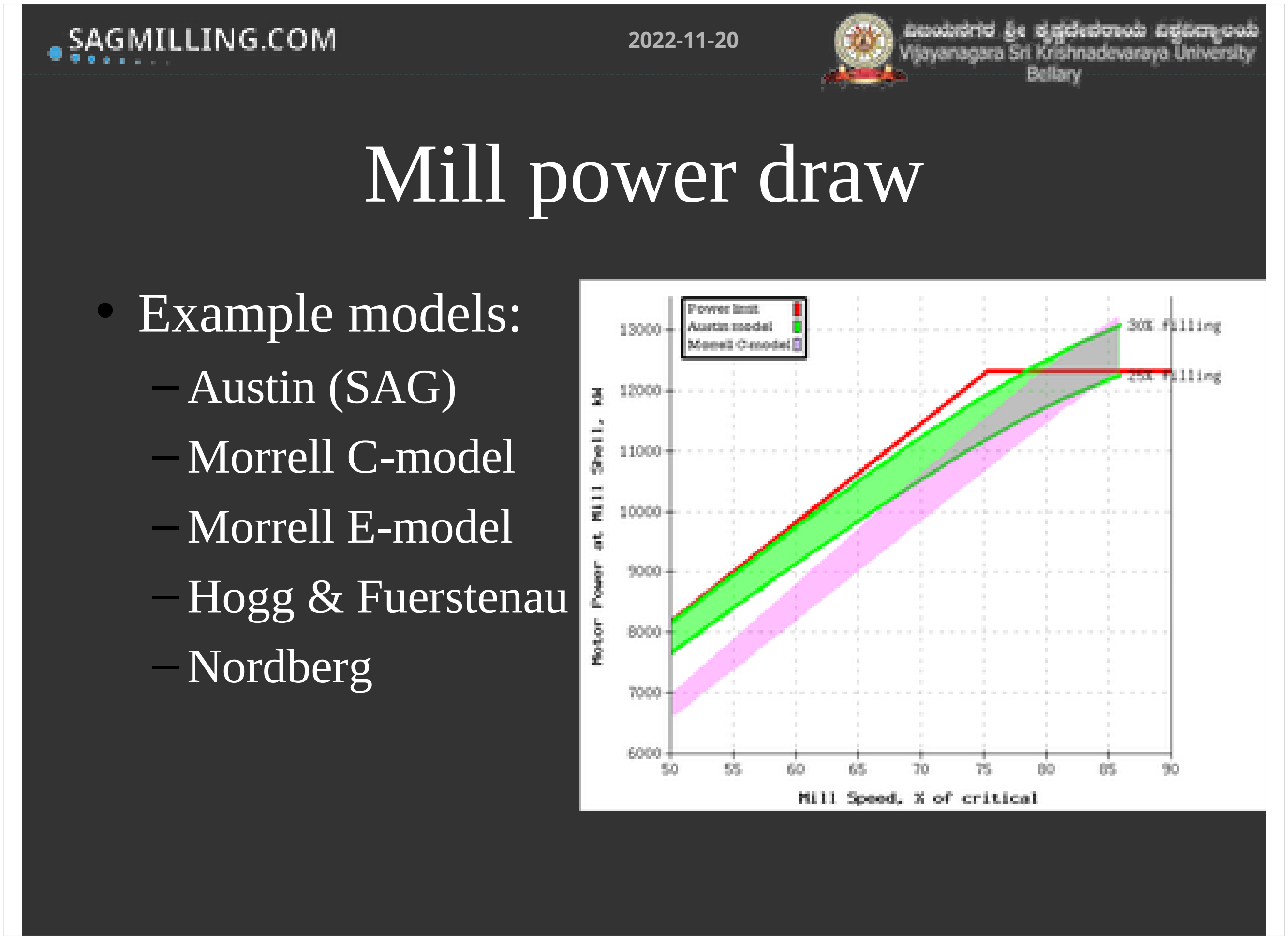
S. Morrell, 1996

The power term *P* is also generated by empirical (or semi-empirical) models. The key parts of a power draw model are:

- mill geometry (diameter inside liners, effective grinding length)
- charge geometry (volumetric filling)
- charge density (ball filling, ore density, slurry percent solids)
- mill rotation speed

Models typically compute some sort of rotating physics geometry (Eg. the lever-arm torque) and then adds empirical factors based on measurements from a variety of mills. Many unmeasured parameters are lumped into these empirical factors, such as the effect of lifter shape and angle.

Power draw should always be predicted relative to the shell of the mill.



SAGMILLING.COM

2022-11-20

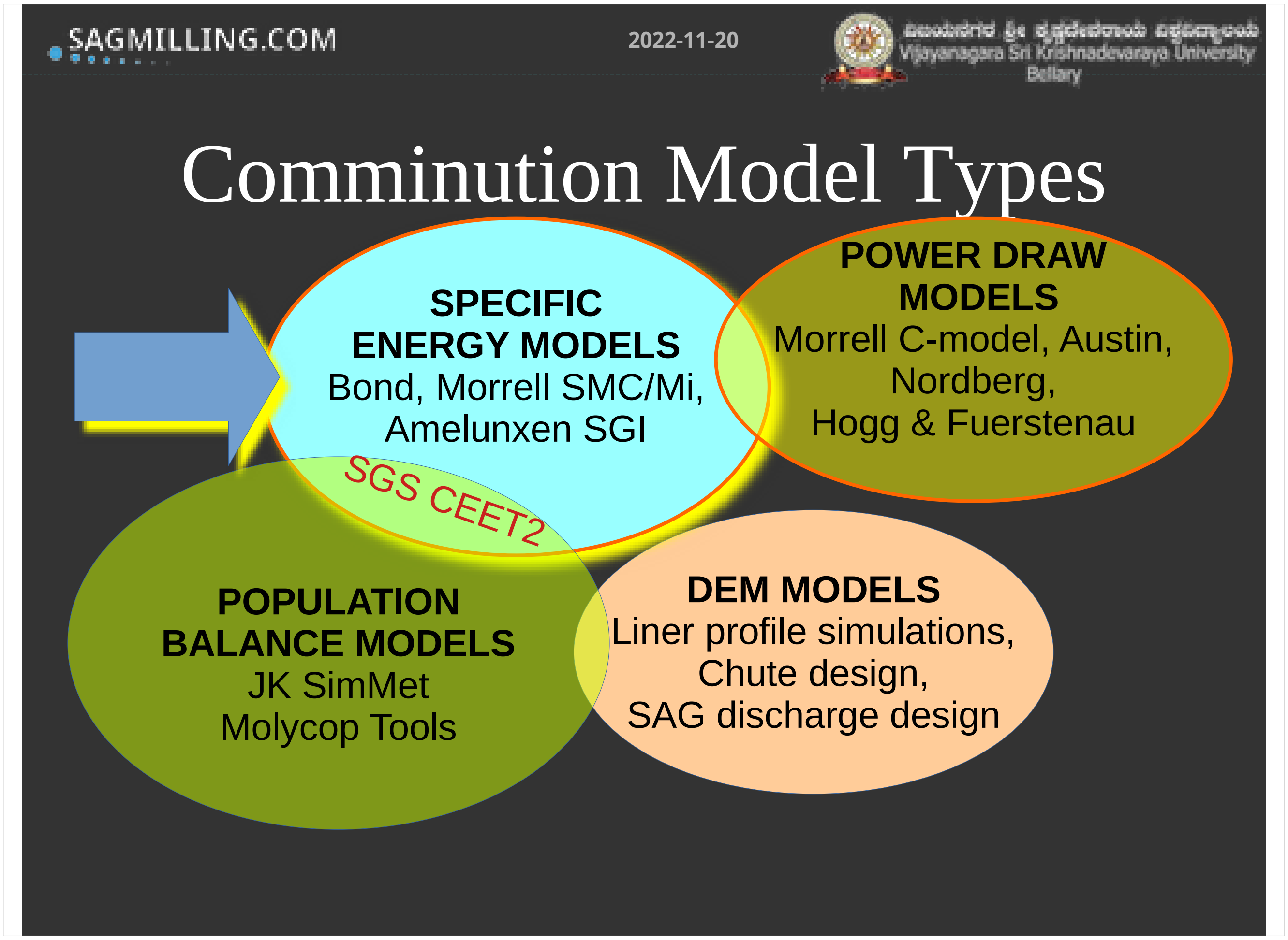
Vijayanagara Sri Krishnadevaraya University
Bellary

Mill power draw

- Example models:
  - Austin (SAG)
  - Morrell C-model
  - Morrell E-model
  - Hogg & Fuerstenau
  - Nordberg

Deviation in model predictions is due simplifying assumptions made in certain models (Eg. charge density in Austin model) and the empirical calibration dataset used. It is a good practise to consider the range of power draw predicted due to a “process control allowance”, the normal variation in a mill where the charge level can rise & fall during operation.

These models can also be used for benchmarking an existing mill – if the models predict a higher power draw than is observed, then the mill is not operating well and an optimization program should be considered to lift the power draw to match the benchmark.



SAGMILLING.COM

2022-11-20

Vijayanagara Sri Krishnadevaraya University
Bellary

Comminution Model Types

SPECIFIC ENERGY MODELS
Bond, Morrell SMC/Mi,
Amelunxen SGI

POWER DRAW MODELS
Morrell C-model, Austin,
Nordberg,
Hogg & Fuerstenau

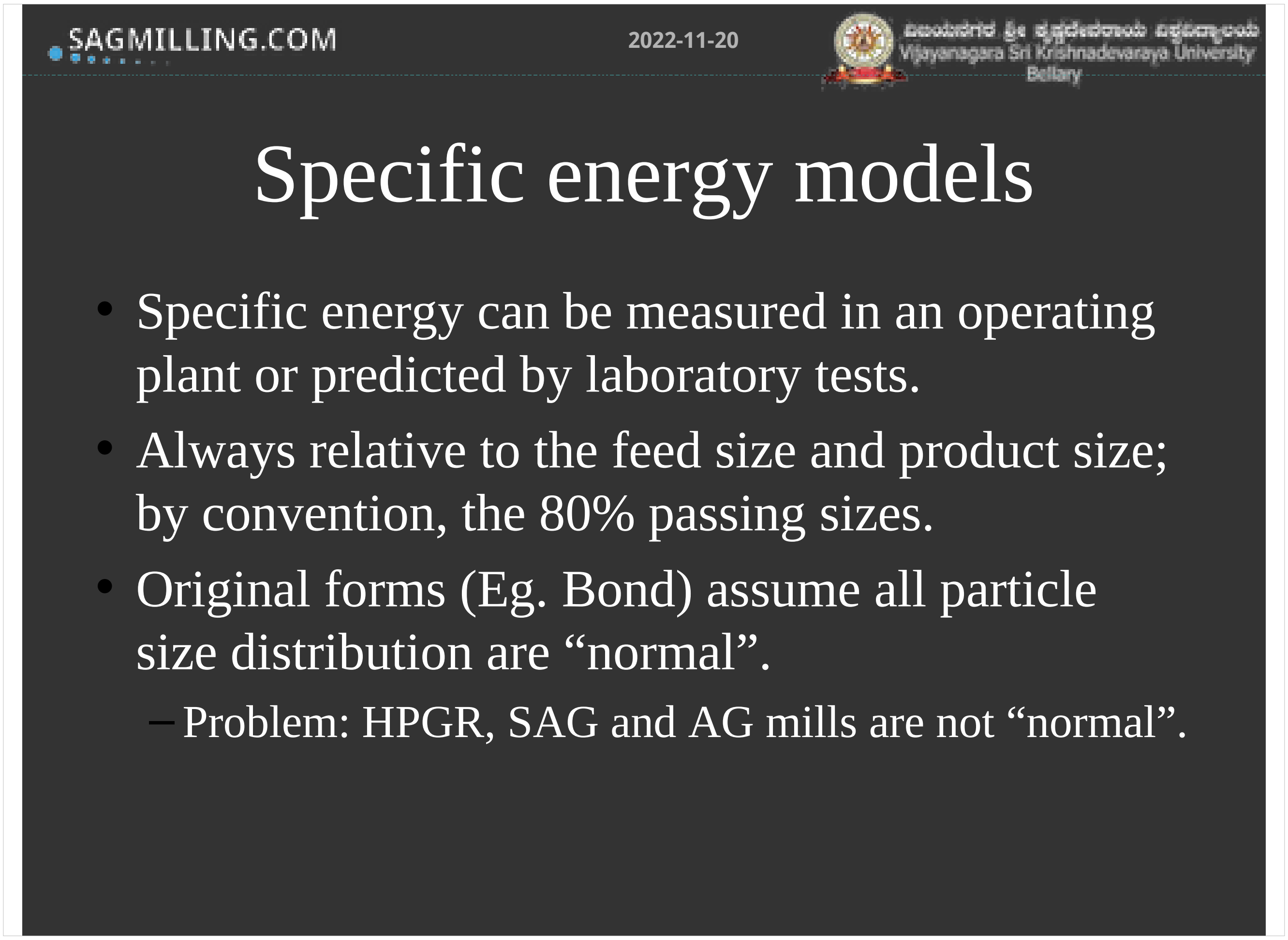
SGS CEET2

POPULATION BALANCE MODELS
JK SimMet
Molycop Tools

DEM MODELS
Liner profile simulations,
Chute design,
SAG discharge design

Modelling of comminution systems can usually be classified into four categories:

- **Power draw models.** Predicts how much power will be drawn by a mill of a specified geometry with a particular charge geometry & density.
- **Specific Energy models.** These assume 'standard' particle size distributions and require only a single size point (usually 80% passing) to characterise an entire particle size distribution. Simple and mostly linear models, they can be run very quickly using computers.
- **Population balance models.** These track flows of individual size classes separately and operate well in situations where “non-standard” particle size distributions are being used. Models tend to have a large number of configuration parameters that make them suitable for optimisation of an existing mill, but provide too many degrees of freedom for early design work.
- **Descrete element models (DEM).** These use fundamental physics to model the motion of simulated particles in a gravity field, and use complex collision calculations to predict the motion of particles as they move within, for example, a turning mill. More complex calculations than other models, these are suited only to detailed design of components of a milling system, such as the lifter face angle and height.



SAGMILLING.COM

2022-11-20

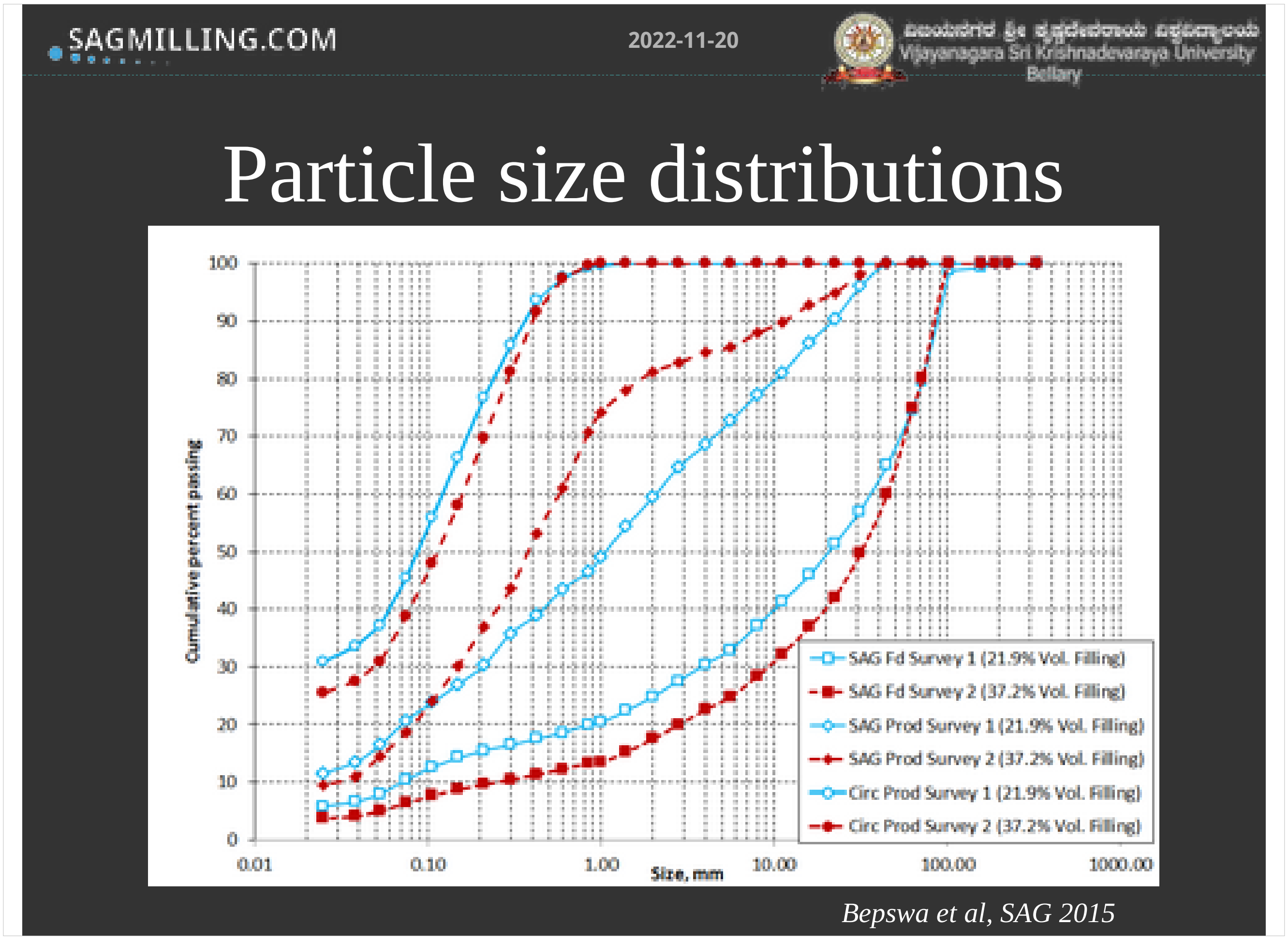
Vijayanagara Sri Krishnadevaraya University
Bellary

Specific energy models

- Specific energy can be measured in an operating plant or predicted by laboratory tests.
- Always relative to the feed size and product size; by convention, the 80% passing sizes.
- Original forms (Eg. Bond) assume all particle size distribution are “normal”.
  - Problem: HPGR, SAG and AG mills are not “normal”.

The laboratory tests that predict *E* should be within about 5% to 10% of each other, but some tests can be confused by particular ore types. Always run (at least) two methods just in case your ore is “special”.

A “normal” particle size distribution is one where you can “shift” the comminution device feed size distribution and the shifted curve looks like the actual product size distribution curve. Put another way, the slope of the particle size curves of the feed and the product are the same. This property applies for “classical” devices like ball mills, rod mills and cone crushers, but doesn’t apply to AG and SAG mills or to HPGRs. These “modern” devices generally create more fines.



SAGMILLING.COM

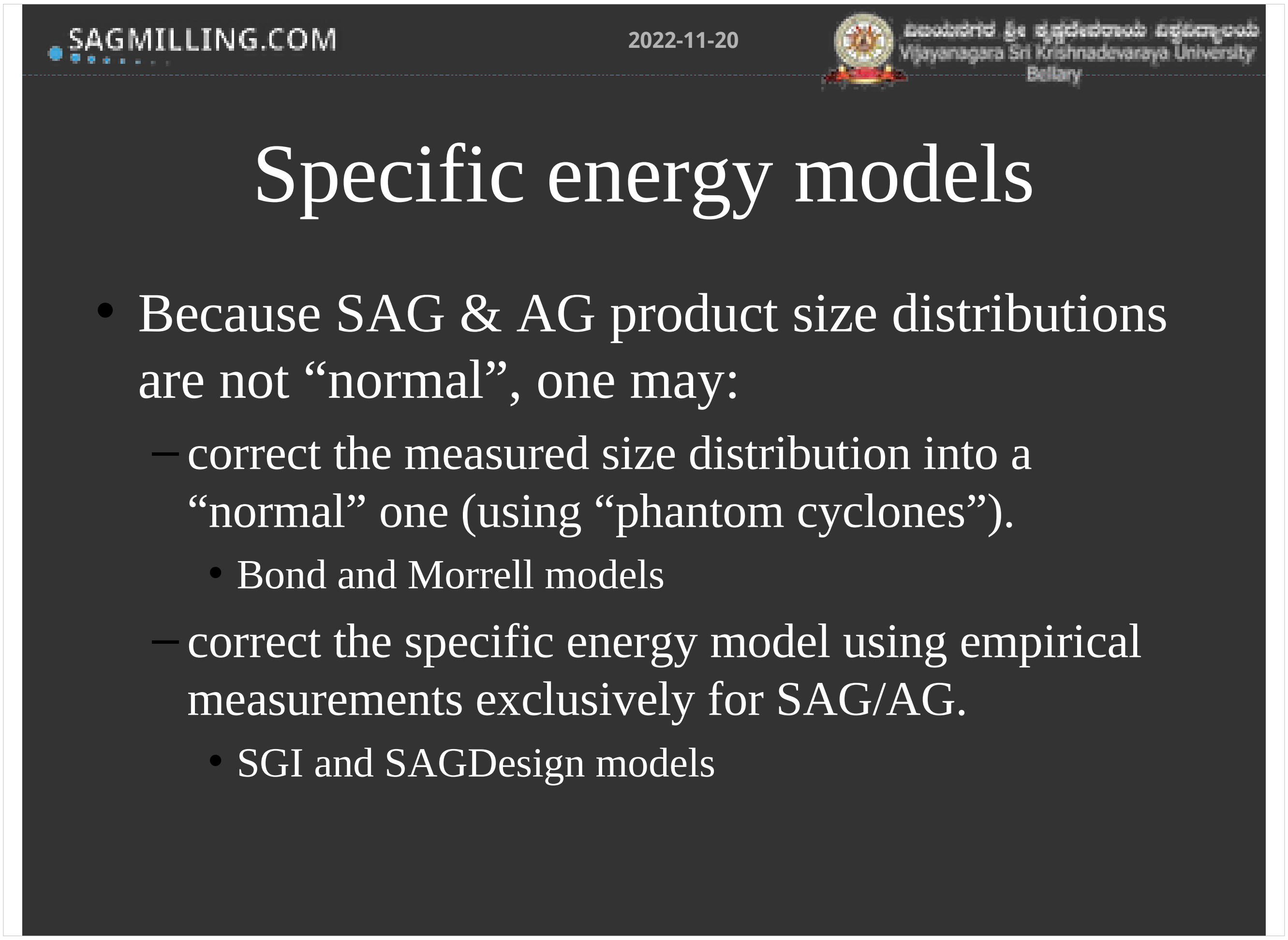
2022-11-20

Vijayanagara Sri Krishnadevaraya University
Bellary

Particle size distributions

Bepswa et al, SAG 2015

Morrell (2011) and Barratt (1989) give good accounts of the issues associated with correcting industrial particle size distributions and making them suitable for modelling. Barratt's solution is to perform what is now known as a "phantom cyclone" correction of AG/SAG product to make the distribution "normal" (he called it a "reduced recovery" calculation). Morrell's method is to concoct a new specific energy equation for SAG & AG milling that does not include the product size as a parameter.



SAGMILLING.COM

2022-11-20

Vijayanagara Sri Krishnadevaraya University
Bellary

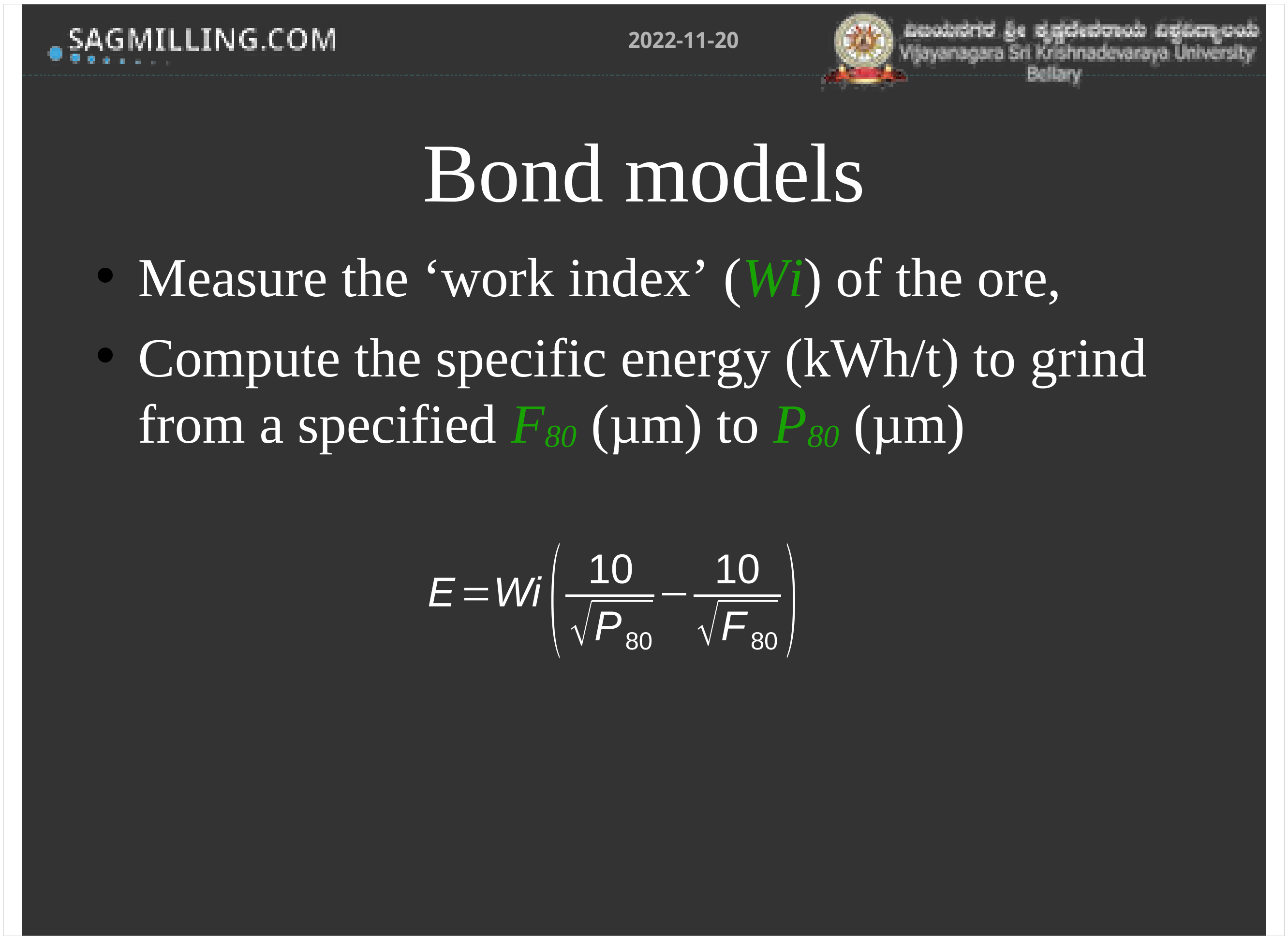
Specific energy models

- Because SAG & AG product size distributions are not "normal", one may:
  - correct the measured size distribution into a "normal" one (using "phantom cyclones").
    - Bond and Morrell models
  - correct the specific energy model using empirical measurements exclusively for SAG/AG.
    - SGI and SAGDesign models

Given that "modern" comminution devices do not conform to a key assumption that underpins "classical" models, the options are to create new models, or re-calibrate the old ones.

Several Bond-based SAG & AG models exist where "calibration factors" are applied to match observations of mills. These allow the "old" tests to be re-purposed for the "new" types of mills.

Alternatively, new tests that mimic the unusual size distributions can be used with new models. The SAG Grindability Index (SGI), SAG Power Index (SPI™) and SAGDesign methods are new tests with associated models that are fit to "standardly abnormal" size distributions one expects in SAG and AG milling.



SAGMILLING.COM

2022-11-20

Vijayanagara Sri Krishnadevaraya University
Bellary

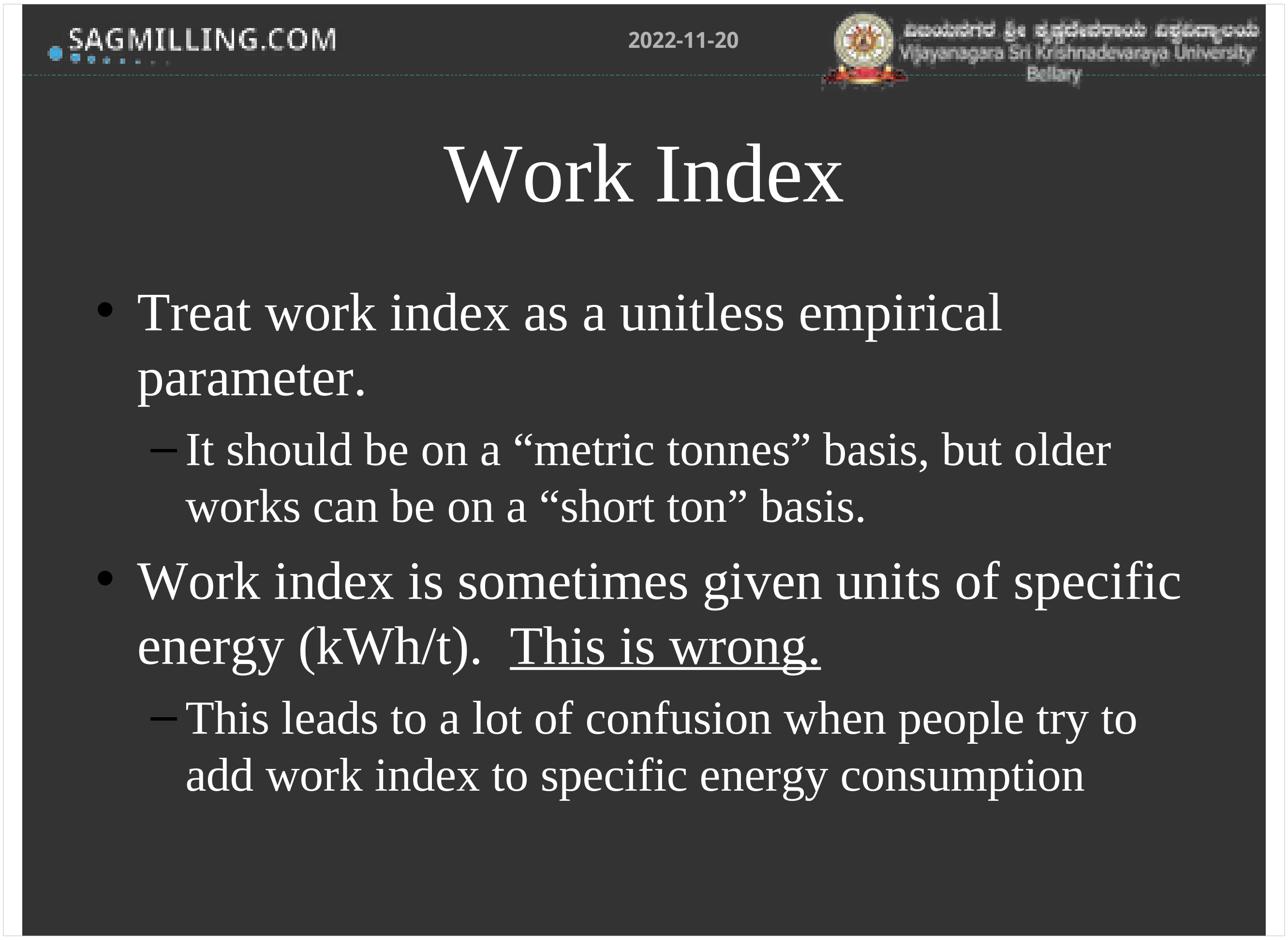
Bond models

- Measure the 'work index' (*Wi*) of the ore,
- Compute the specific energy (kWh/t) to grind from a specified F_{80} (μm) to P_{80} (μm)

$$E = Wi\left(\frac{10}{\sqrt{P_{80}}} - \frac{10}{\sqrt{F_{80}}}\right)$$

Introduced as "the Third Theory" by Fred Bond in 1952, the model was created when data collected by the Allis Chalmers company during the 1930s and 1940s did not seem to fit the two mineral breakage models known of the time: Von Rittinger and Kick.

The model is empirical, and was generated by plotting about a hundred survey data points on log-log graph paper and then eyeballing a straight line through the cloud of data. The exponent of "one over the square root" is the same as an exponent of –½, which was the slope that Bond measured of his eyeballed straight line.



SAGMILLING.COM

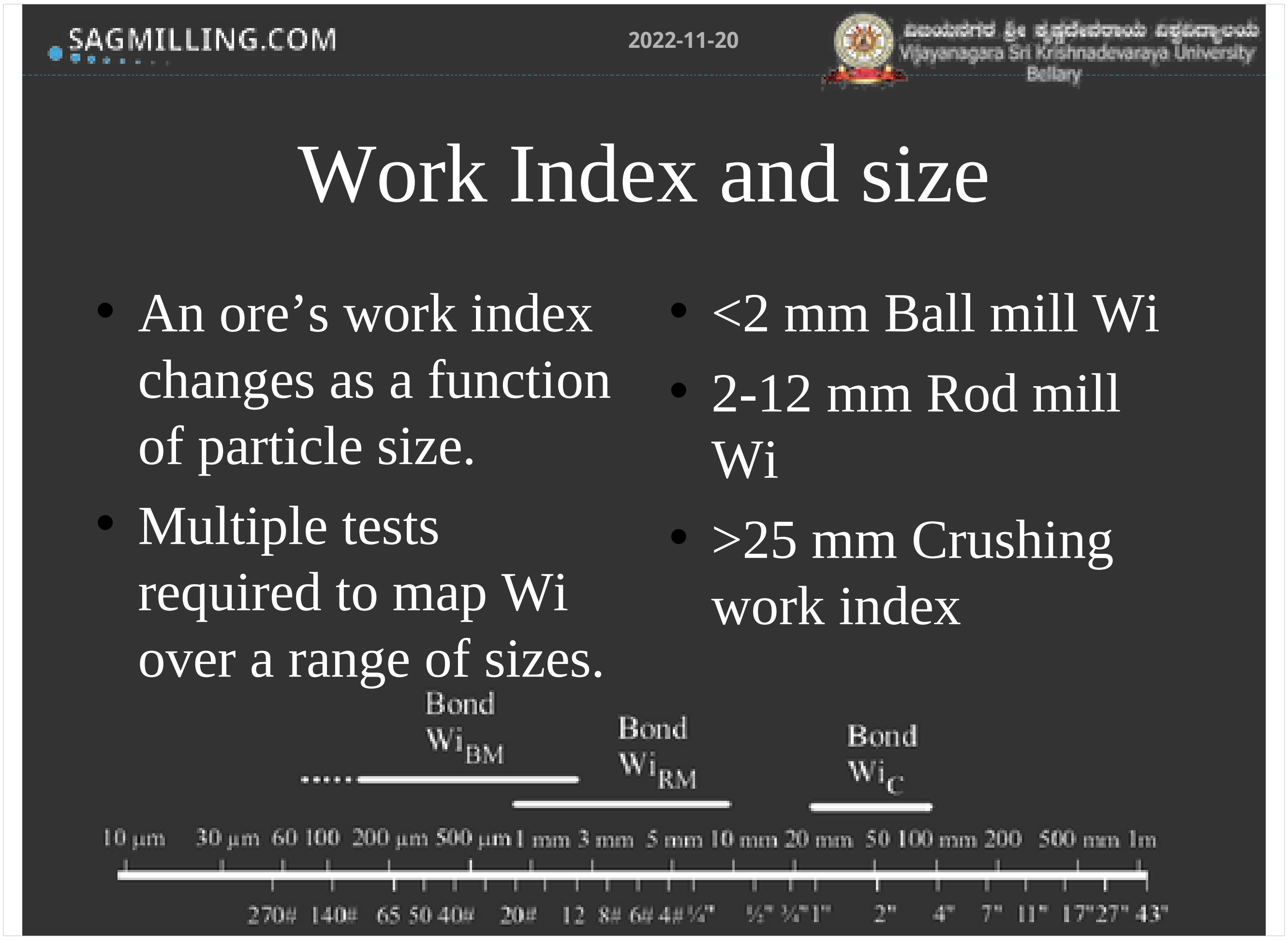
2022-11-20

Vijayanagara Sri Krishnadevaraya University
Bellary

Work Index

- Treat work index as a unitless empirical parameter.
  - It should be on a “metric tonnes” basis, but older works can be on a “short ton” basis.
- Work index is sometimes given units of specific energy (kWh/t). This is wrong.
  - This leads to a lot of confusion when people try to add work index to specific energy consumption

The SAG2019 paper I authored with Berge Simonian rants about this and offers a more academic answer to what the units should be for people not happy with the ‘unitless emperical parameter’ argument.



SAGMILLING.COM 2022-11-20

Vijayanagara Sri Krishnadevaraya University
Bellary

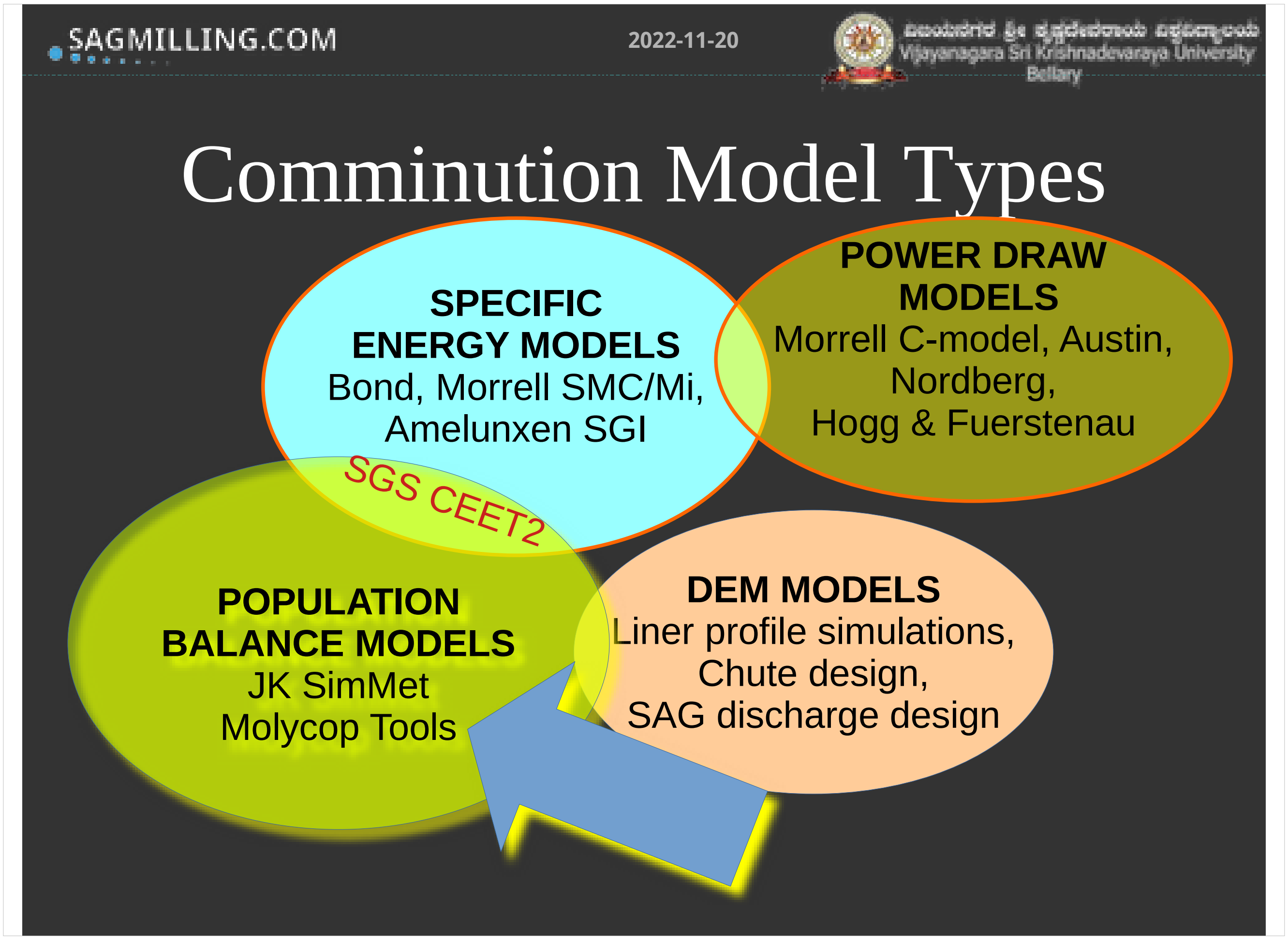
Work Index and size

- An ore’s work index changes as a function of particle size.
- Multiple tests required to map Wi over a range of sizes.
- <2 mm Ball mill Wi
- 2-12 mm Rod mill Wi
- >25 mm Crushing work index

Other tests that overlap the Bond Wi_{RM} size range include:

- SPI™ or SGI (SAG Grindability Index)
- SAGDesign
- SMC Test™

The JK Drop Weight Test covers the Wi_{RM} range up into the Wi_{C} range. It is an expensive test, but generates a lot of useful data.



SAGMILLING.COM

2022-11-20

Vijayanagara Sri Krishnadevaraya University
Bellary

Comminution Model Types

SPECIFIC ENERGY MODELS
Bond, Morrell SMC/Mi, Amelunxen SGI

POWER DRAW MODELS
Morrell C-model, Austin, Nordberg, Hogg & Fuerstenau

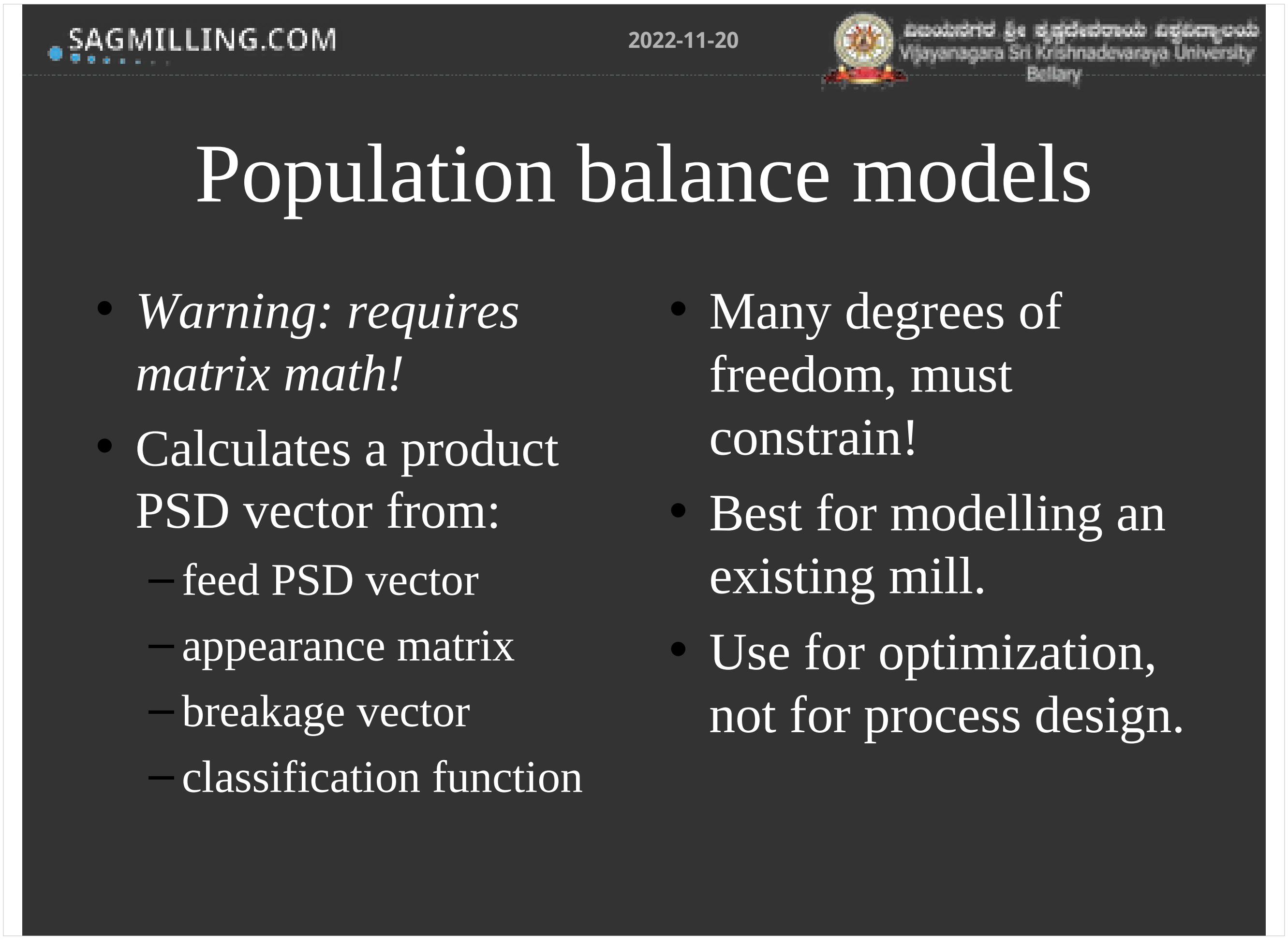
SGS CEET2

POPULATION BALANCE MODELS
JK SimMet
Molycop Tools

DEM MODELS
Liner profile simulations, Chute design, SAG discharge design

Modelling of comminution systems can usually be classified into four categories:

- **Power draw models.** Predicts how much power will be drawn by a mill of a specified geometry with a particular charge geometry & density.
- **Specific Energy models.** These assume 'standard' particle size distributions and require only a single size point (usually 80% passing) to characterise an entire particle size distribution. Simple and mostly linear models, they can be run very quickly using computers.
- **Population balance models.** These track flows of individual size classes separately and operate well in situations where “non-standard” particle size distributions are being used. Models tend to have a large number of configuration parameters that make them suitable for optimisation of an existing mill, but provide too many degrees of freedom for early design work.
- **Descrete element models (DEM).** These use fundamental physics to model the motion of simulated particles in a gravity field, and use complex collision calculations to predict the motion of particles as they move within, for example, a turning mill. More complex calculations than other models, these are suited only to detailed design of components of a milling system, such as the lifter face angle and height.



SAGMILLING.COM

2022-11-20

Vijayanagara Sri Krishnadevaraya University
Bellary

Population balance models

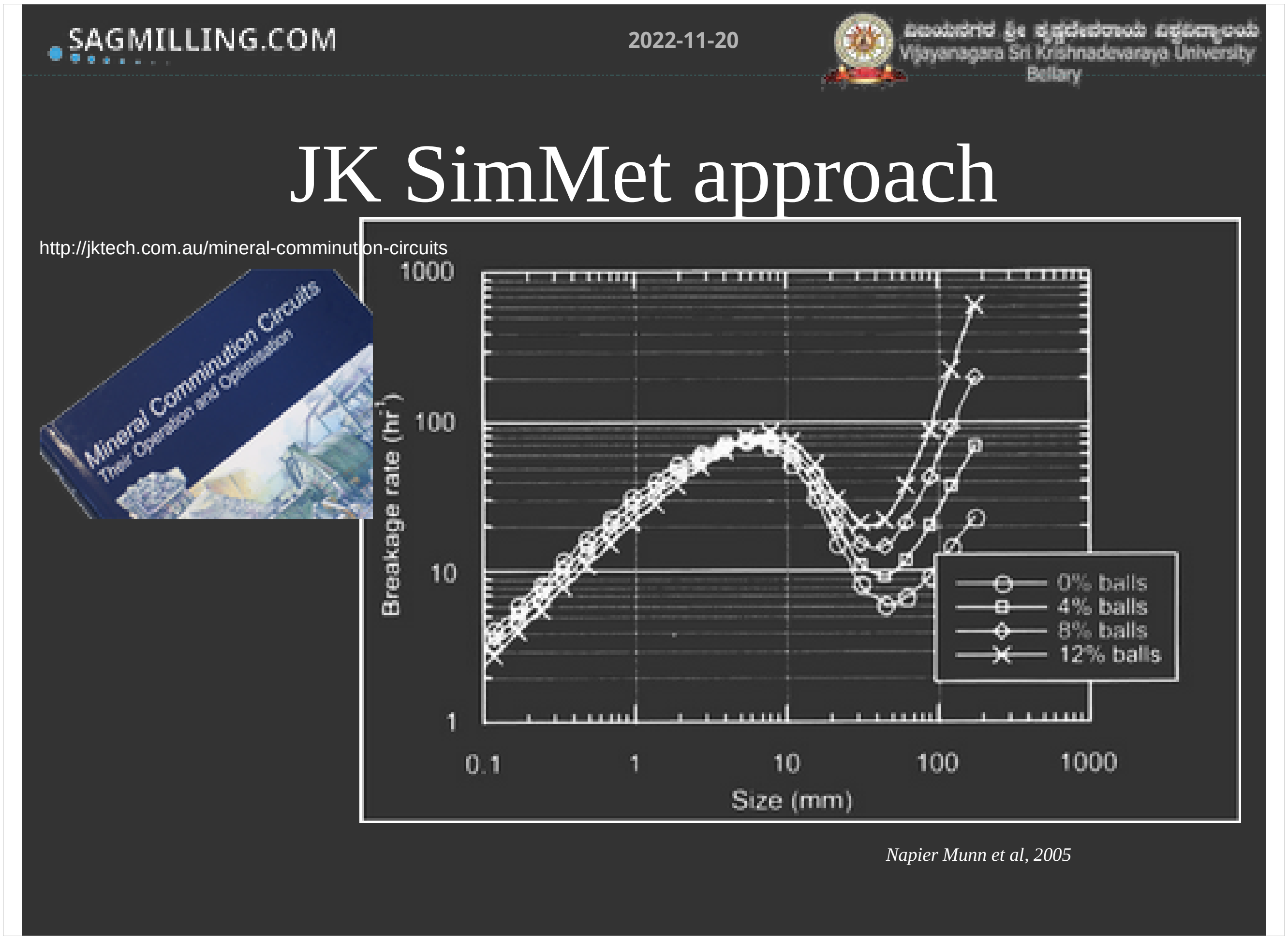
- *Warning: requires matrix math!*
- Calculates a product PSD vector from:
  - feed PSD vector
  - appearance matrix
  - breakage vector
  - classification function
- Many degrees of freedom, must constrain!
- Best for modelling an existing mill.
- Use for optimization, not for process design.

The breakage cycle roughly looks like this (in element form):

$$F_i+\sum_{j=1}^{i} a_{ij} r_j s_j = P_i + r_i s_i$$

Where F is the feed, a is the appearance matrix, r is the breakage rate vector, s is mass of size j in the mill charge, and P is the product determined by a classification function (particles passing out the discharge grate).

An important assumption is that the appearance matrix a is the same for all sizes, and can be estimated using drop weight test results such as the diagram above. The breakage rates r are generally a machine characteristic and must be measured.


SAGMILLING.COM

2022-11-20

Vijayanagara Sri Krishnadevaraya University
Bellary

JK SimMet approach

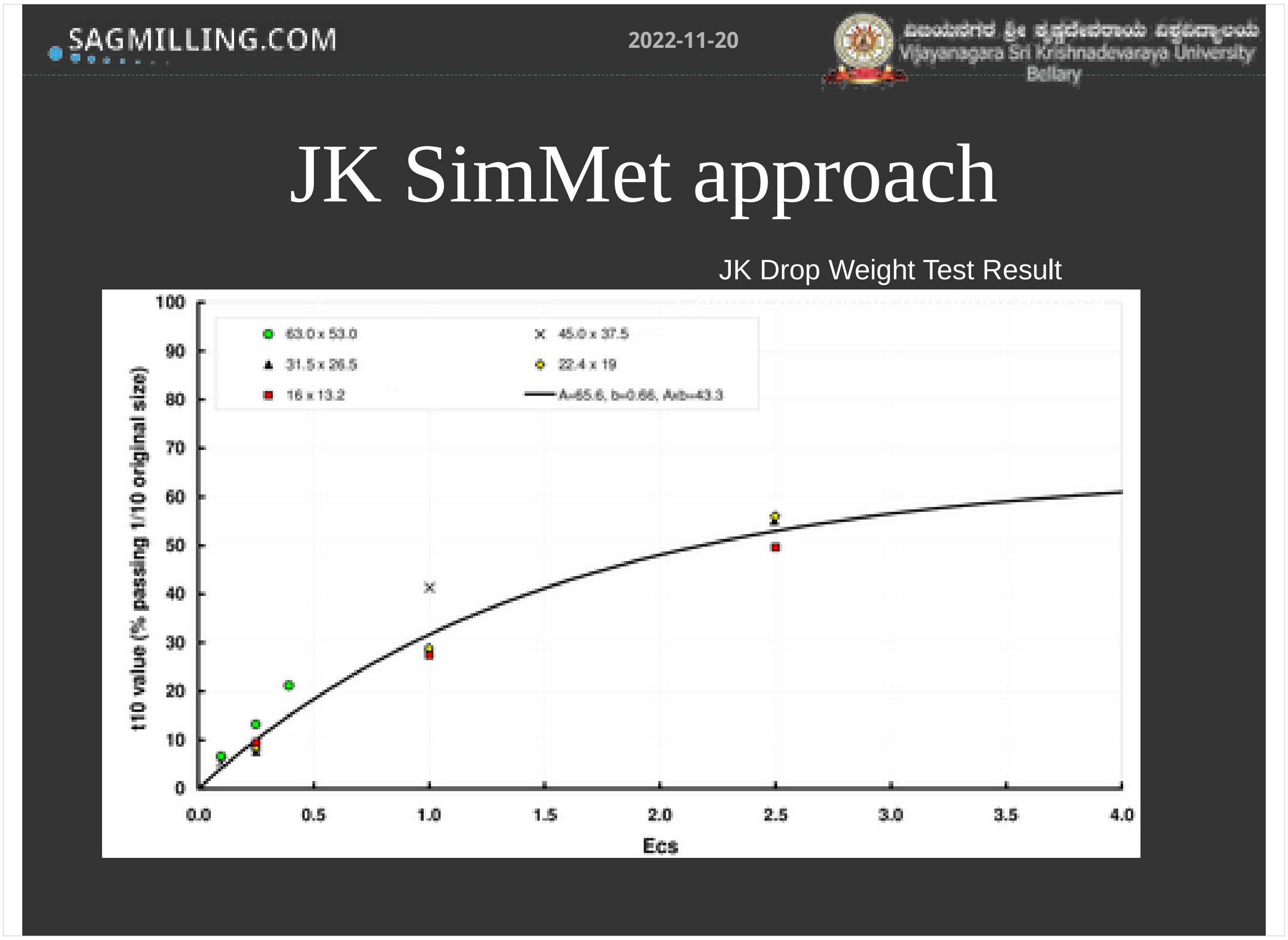
http://jktech.com.au/mineral-comminution-circuits

Napier Munn et al, 2005

JK SimMet is used for mill modelling for optimization of operations and design. It has a simple flowsheet-like interface for constructing circuits, but the underlying mathematics are extremely sophisticated.

This is both a blessing and a curse – the software looks easy to use, but understanding the math and models is critical to getting sensible results. The breakage rate vector can be adjusted based on changes in grinding conditions, such as the example above where the effect of changes ball charge can be simulated by varying the “spline knots” in the vector.

Many training courses are available for this software; they are *highly* recommended. Also avoid very sophisticated modelling until you have a *lot* of experience with the models.



SAGMILLING.COM

2022-11-20

Vijayanagara Sri Krishnadevaraya University
Bellary

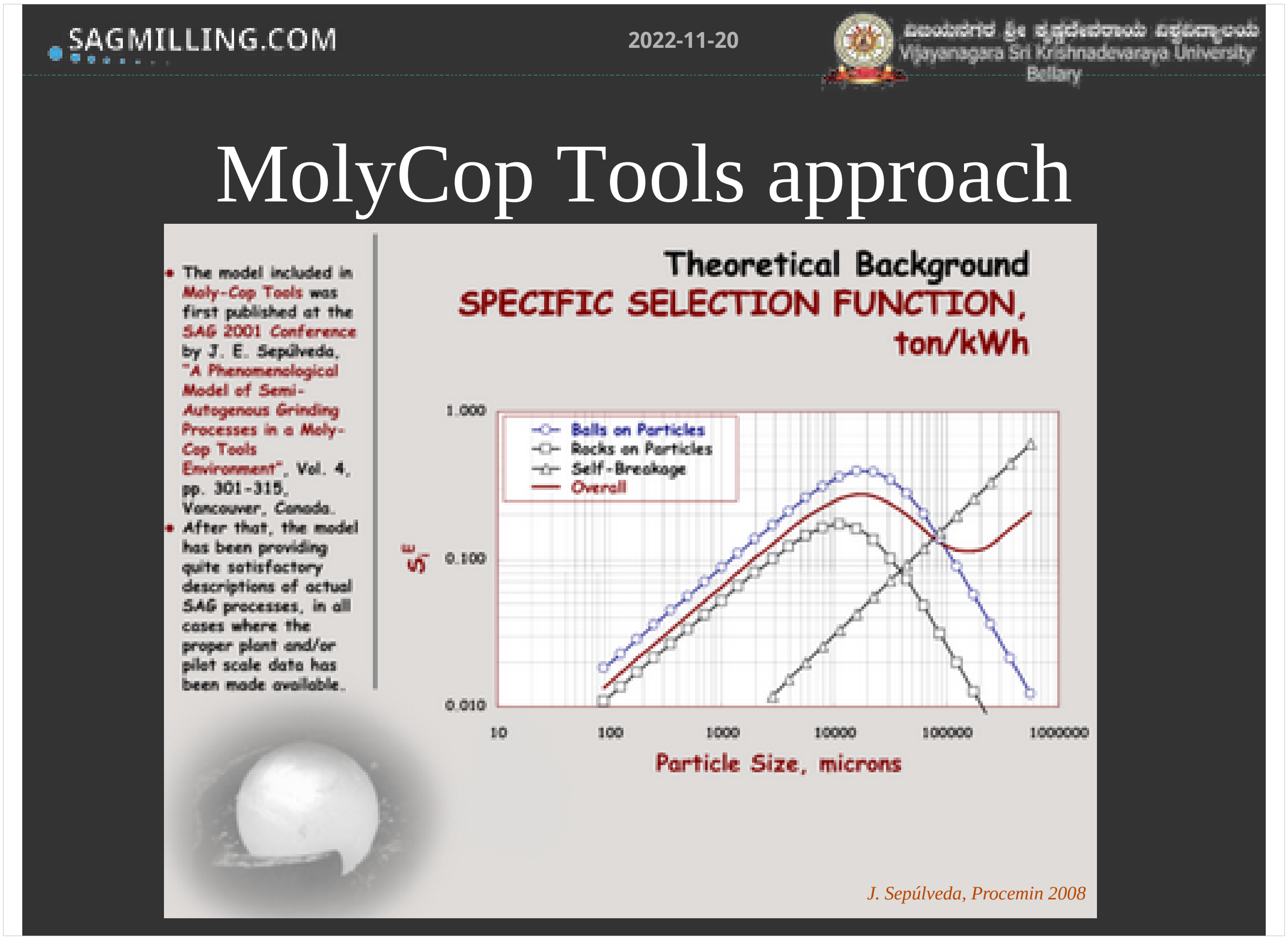
JK SimMet approach

JK Drop Weight Test Result

One of the key features of JK SimMet is the ability to construct an appearance matrix given only laboratory testwork. The “drop weight test” is interpreted to generate the lower-triangular appearance matrix used in the breakage equation. This is valuable for modelling new orebodies.

But this also highlights a simplifying assumption in this type of model, that all particles break into the same smaller materials:

- 71% of its original size,
- 50% of its original size,
- 35% of its original size,
- 25% of its original size, and so on...



SAGMILLING.COM

2022-11-20

Vijayanagara Sri Krishnadevaraya University
Bellary

MolyCop Tools approach

- The model included in *Moly-Cop Tools* was first published at the *SAG 2001 Conference* by J. E. Sepúlveda, *"A Phenomenological Model of Semi-Autogenous Grinding Processes in a Moly-Cop Tools Environment"*, Vol. 4, pp. 301-315, Vancouver, Canada.
- After that, the model has been providing quite satisfactory descriptions of actual SAG processes, in all cases where the proper plant and/or pilot scale data has been made available.

Theoretical Background

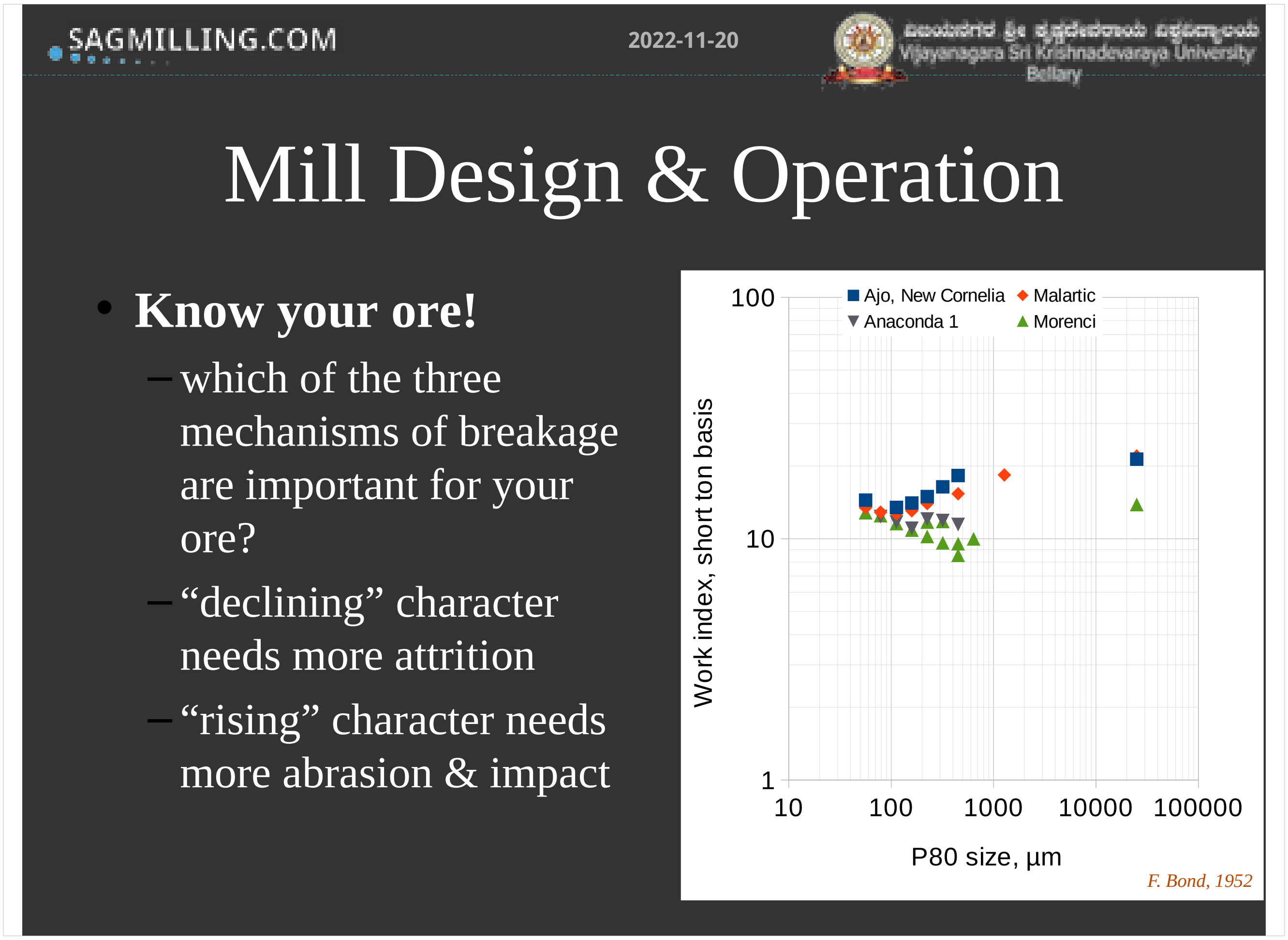
SPECIFIC SELECTION FUNCTION, ton/kWh

J. Sepúlveda, Procemin 2008

MolyCop Tools is a spreadsheet-based package that includes a lot of tools for performing and interpreting mill surveys. You can’t use this function of MolyCop Tools for design work (but there are Bond-based tools suitable for design).

Both the *breakage function* (appearance matrix) and *specific selection function* (breakage rates) are computed based on a mill survey using the Microsoft Excel *Solver* function. It includes population balance curve fitting that separates the effect of ball-ore collisions, ore-ore collisions and self-breakage.

Contact MolyCop to request a copy. Attending a training course is *highly* recommended.



SAGMILLING.COM

2022-11-20

Vijayanagara Sri Krishnadevaraya University
Bellary

Mill Design & Operation

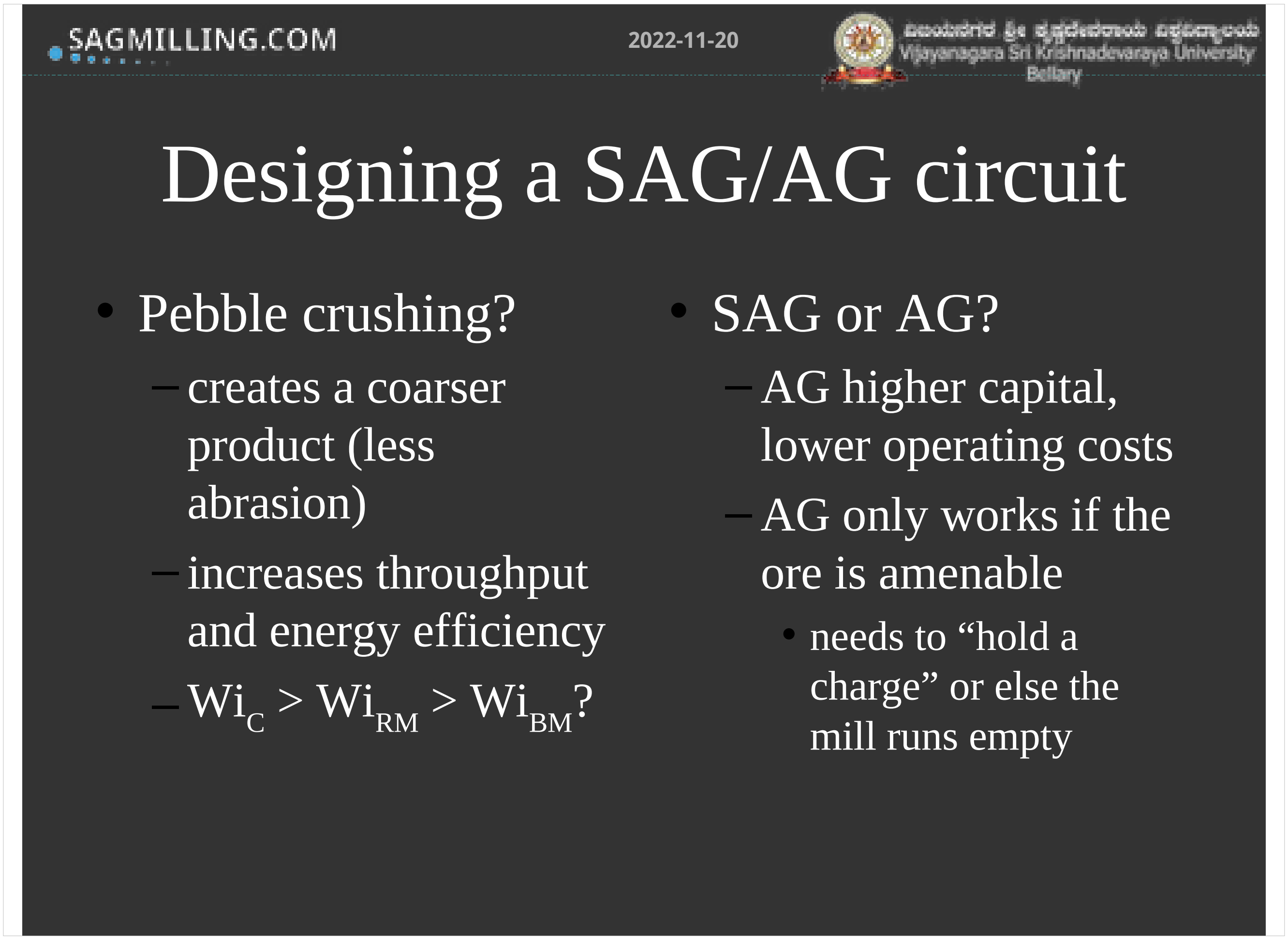
- **Know your ore!**
  - which of the three mechanisms of breakage are important for your ore?
  - “declining” character needs more attrition
  - “rising” character needs more abrasion & impact

F. Bond, 1952

Any ore will “want” to break a certain way, and the most efficient comminution circuits will be those that exploit the rock’s preferred breakage.

In general, more competent ores require more “crushing”; these are the typical greenstone (Abitibi) or Western Australian ores. Less competent ores easily break into pebble sizes and then become harder.

The diagram above uses a Bond work index metric across sizes; you can observe this by performing the three Bond work index tests (ball mill, rod mill & crushing) or you can use a different metric like cumulative specific energy by size (Hukki’s Conjecture).



SAGMILLING.COM

2022-11-20

Vijayanagara Sri Krishnadevaraya University
Bellary

Designing a SAG/AG circuit

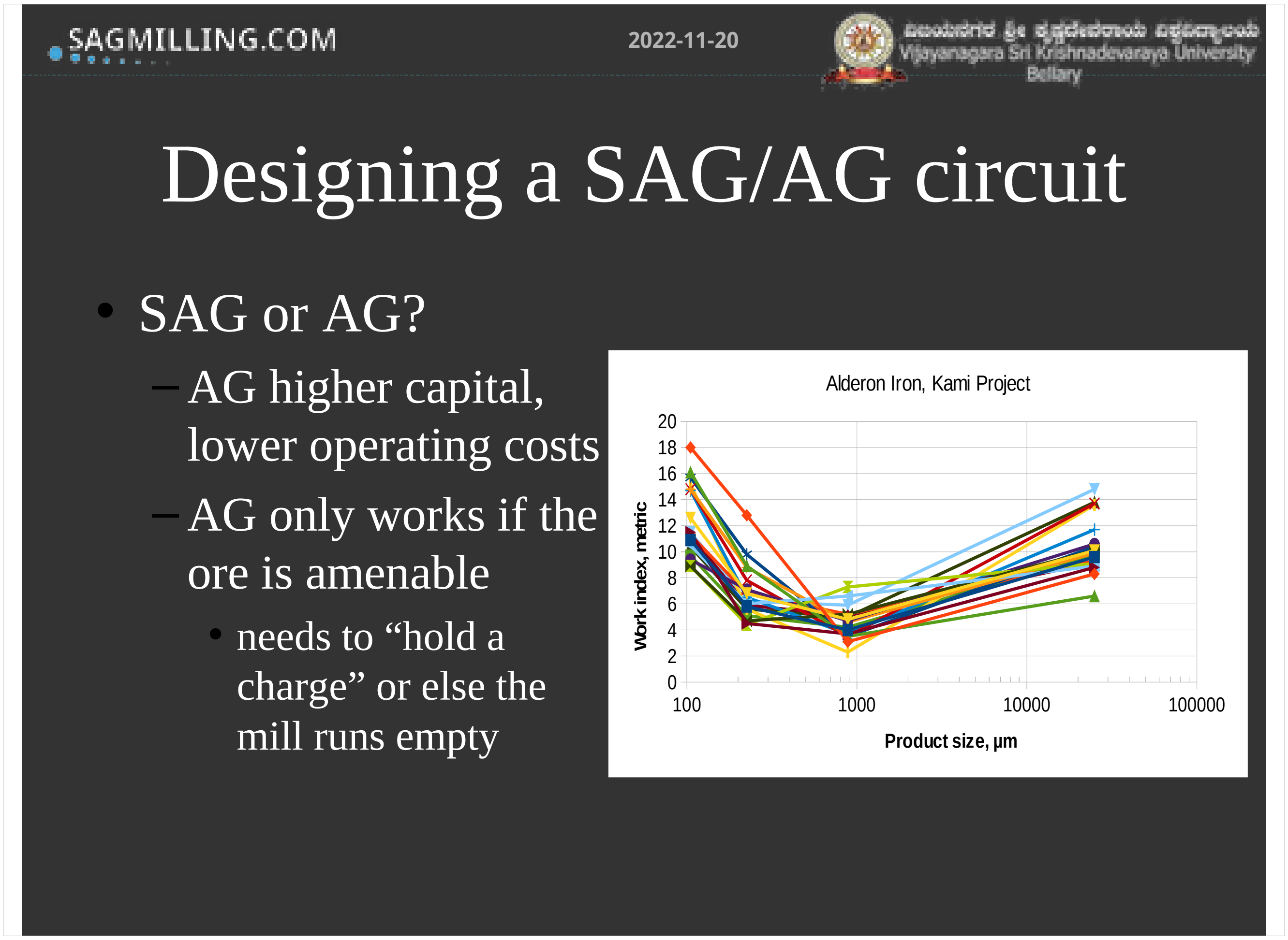
- Pebble crushing?
  - creates a coarser product (less abrasion)
  - increases throughput and energy efficiency
  - $Wi_C > Wi_{RM} > Wi_{BM}$?
- SAG or AG?
  - AG higher capital, lower operating costs
  - AG only works if the ore is amenable
    - needs to “hold a charge” or else the mill runs empty

Pebble crushing is normally used in applications where highest throughput is desired and transfer sizes are coarse. Cordilleran & Andean porphyries are the best examples; big high-tonnage open pits with forgiving flotation characteristics at coarse P_{80}’s.

- Highland Valley Copper, 120 ktpd to 150 ktpd and cyclone overflow P_{80} range 250 µm to 400 µm.

Applications requiring very fine product sizes need more abrasion breakage and less impact. The coarse particles are the grinding media, so don’t go breaking them too soon!

- Selbaie, 5 ktpd and cyclone overflow P_{80} range 40 µm to 60 µm where Wi_C = ?, Wi_{RM} = 16 (metric), Wi_{BM} = 12 @ 104 µm, 13 @ 54 µm (metric).


SAGMILLING.COM

2022-11-20

Vijayanagara Sri Krishnadevaraya University
Bellary

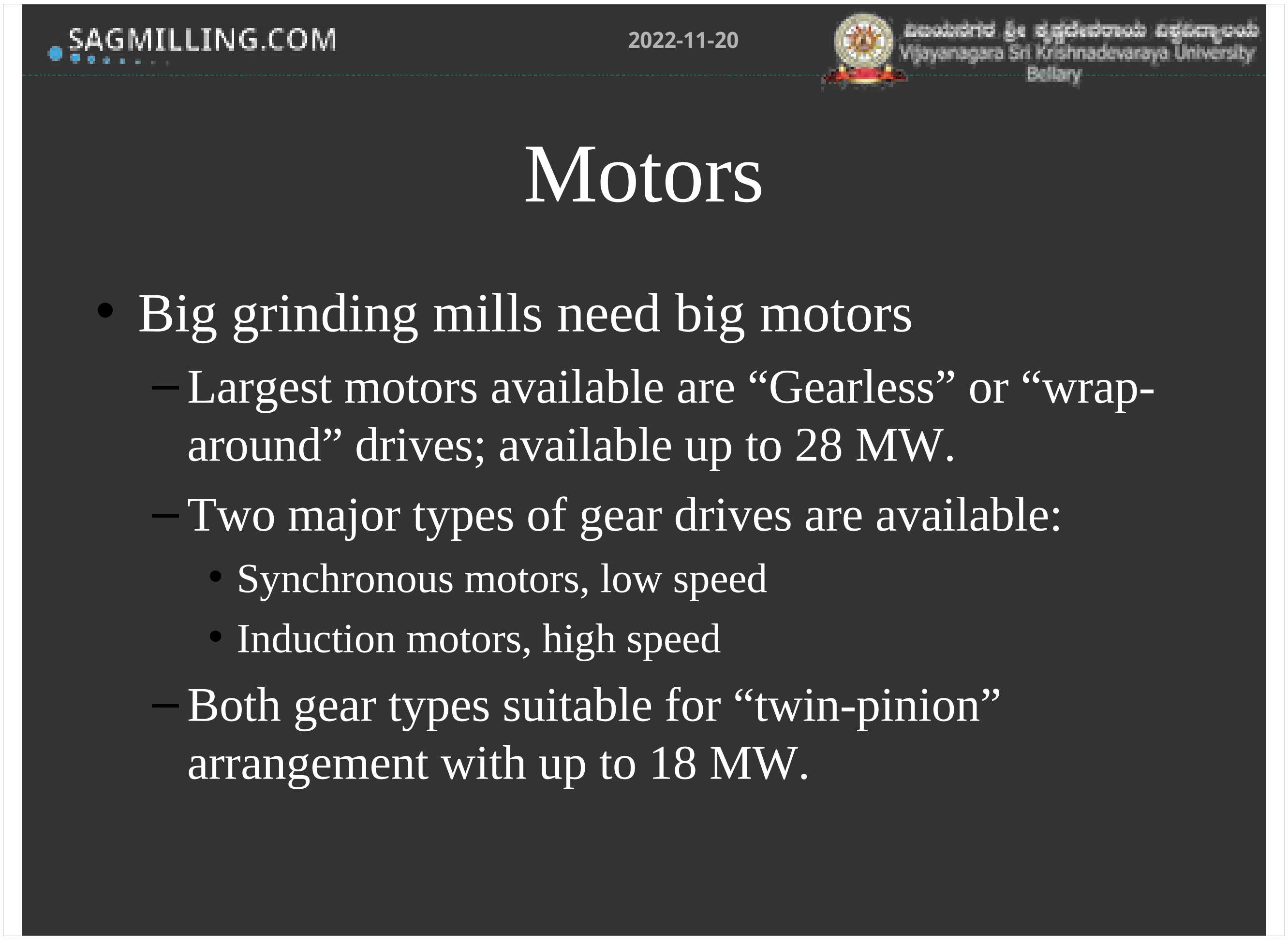
Designing a SAG/AG circuit

- SAG or AG?
  - AG higher capital, lower operating costs
  - AG only works if the ore is amenable
    - needs to “hold a charge” or else the mill runs empty

Example of what should be an AG-amenable ore:

(based on AGD interpretation of Alderon Iron ni43-101 report)

- Want a “mill charge” of coarse material to draw the mill power; the coarse work index (Wi_C) should provide that.
- Don’t want to be overwhelmed with pebbles; the low medium size work index (Wi_{RM}) gives that.
- Finest size range ($2\times Wi_{BM}$) isn’t relevant due to the 1-2 mm transfer size, unless you are doing single-stage AG milling.



SAGMILLING.COM 2022-11-20 Vijayanagara Sri Krishnadevaraya University Bellary

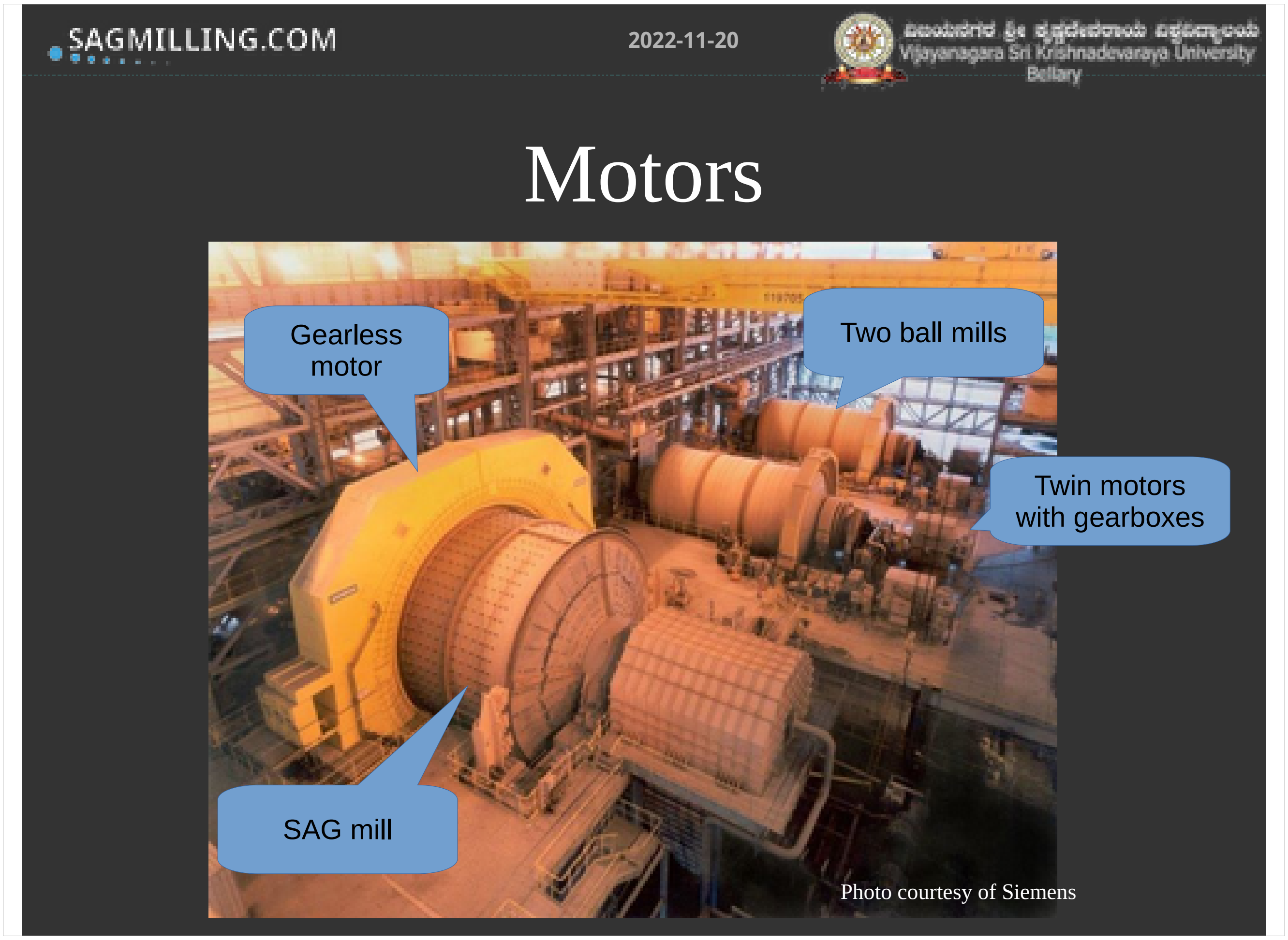
Motors

- Big grinding mills need big motors
  - Largest motors available are “Gearless” or “wrap-around” drives; available up to 28 MW.
  - Two major types of gear drives are available:
    - Synchronous motors, low speed
    - Induction motors, high speed
  - Both gear types suitable for “twin-pinion” arrangement with up to 18 MW.

The biggest motors available are the gearless drives where the motor stator wraps around the mill itself and the motor rotor poles are attached to a flange on the mill. It is essentially a hydroelectric turbine turned inside-out. Gearless drives are inherently variable speed and have high energy efficiency. They are also expensive.

The largest gear drives installed to date are 9 MW per motor, and two can be attached to a mill in a “twin-pinion” arrangement for 18 MW of total power. Gear drives are usually fixed-speed but a variable speed controller can be added to the drive system.

Induction motors are the simplest and have the lowest capital cost, but also have the lowest electromechanical efficiency. Synchronous motors are a good compromise and can be designed to consume reactive power in the plant’s electrical grid.



Motors

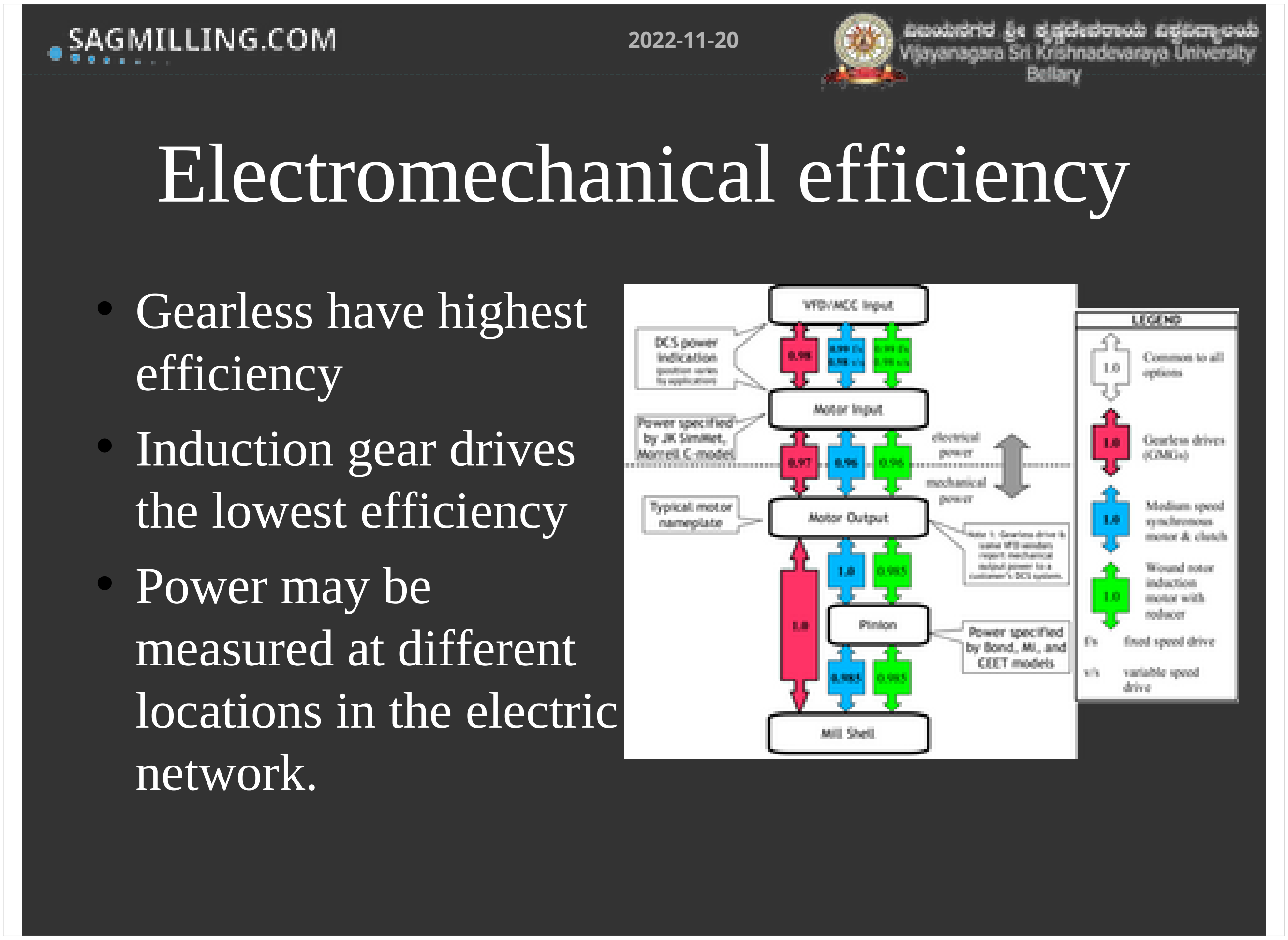
Photo courtesy of Siemens

This photo (courtesy of Siemens) shows a large gearless SAG mill and two ball mills with twin-pinion induction drives. Speed reduction gearboxes are used on the ball mills to convert the high speed motor rotation into a rotation rate suitable for the mill.

As an order-of-magnitude approximation:

- a mill spins at ~10 RPM
- a gearless drive operates at the same ~10 RPM
- a low-speed synchronous motor operates at ~100 RPM
- a high-speed induction motor operates at ~1000 RPM
- a pinion can have 10:1 turn-down (synchronous)
- a gearbox is needed to turn-down another 10:1 (induction)

Note, modern variable speed drives can be cheaper than fixed speed!



SAGMILLING.COM

2022-11-20

Vijayanagara Sri Krishnadevaraya University
Bellary

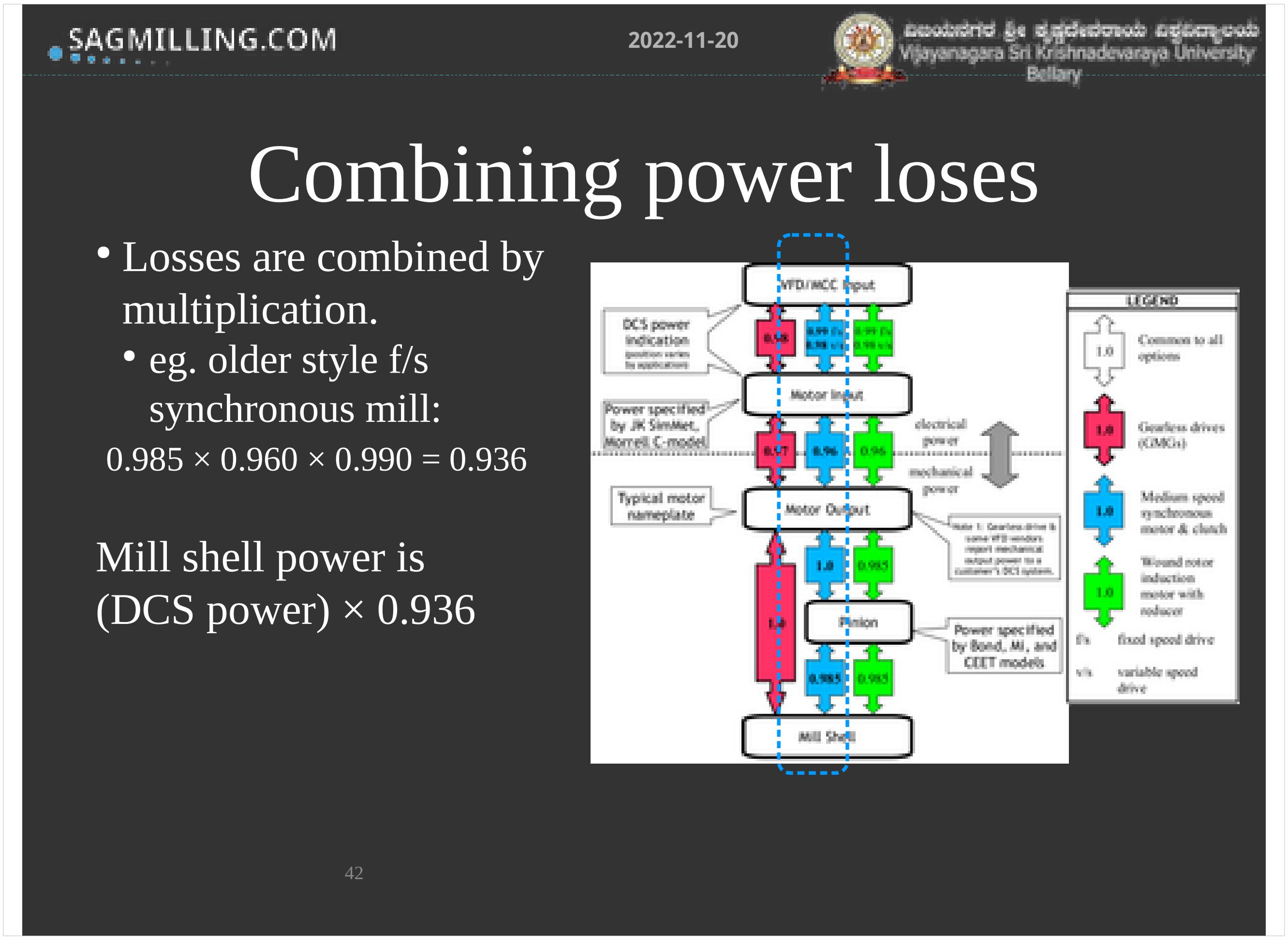
Electromechanical efficiency

- Gearless have highest efficiency
- Induction gear drives the lowest efficiency
- Power may be measured at different locations in the electric network.

Operating cost of electricity is measured at the Utility connection (substation) or at an on-site generator. You must allow for electrical losses at each transformer and other device in the electrical network. See https://www.sagmilling.com/articles/1/view/?s=1

Power factor (reactive power) is an additional energy loss in induction drives that can be "corrected" by adding power factor correcting capacitors to the network.

Harmonics will be introduced into the network by variable frequency drives (rectifier or thyristor-based) and usually require "harmonic filters" in the network.


SAGMILLING.COM

2022-11-20

Vijayanagara Sri Krishnadevaraya University
Bellary

Combining power loses

- Losses are combined by multiplication.
  - eg. older style f/s synchronous mill:

0.985 × 0.960 × 0.990 = 0.936

Mill shell power is (DCS power) × 0.936

42

In this example, a fixed-speed synchronous motor has the power measured at a transformer input. The components of the power losses are:

- the pinion gear mechanical losses (0.985 is the typical value used for all gear drives)

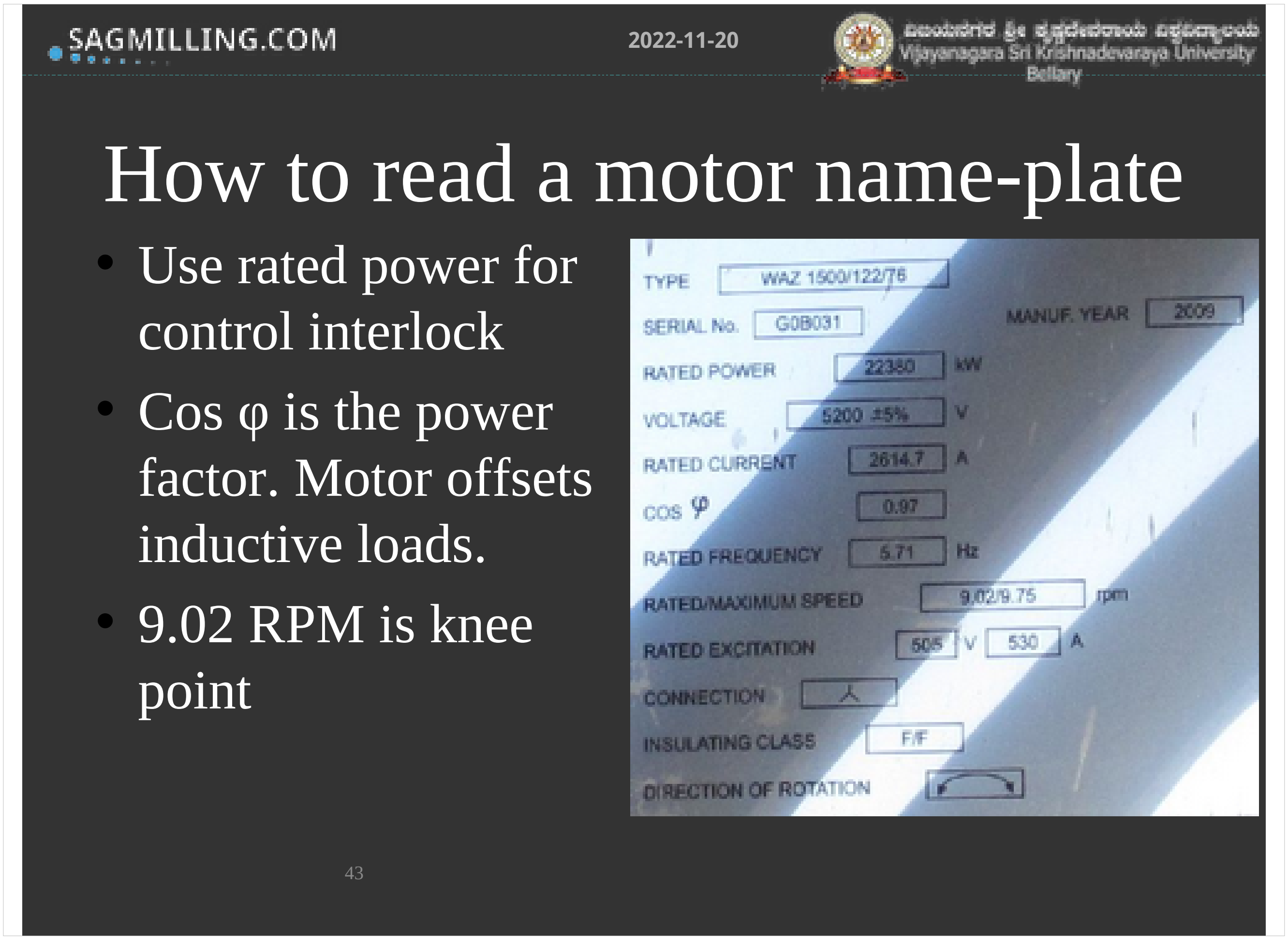
- the motor efficiency (assume 0.96, or read from the motor name-plate)

- the transformer and switchgear losses (assume 0.990)

If a variable speed drive exists (LCI or cycloconverter), then assume 0.980 instead of 0.990 for the “transformer and switchgear losses” above.

This example assumes a “unity power factor” or “cos Φ=1.000”. If a motor has a different power factor, then consult with an electrical specialist to determine the appropriate overall system efficiency value.

Different sources will give slightly different values for these assorted efficiencies. The reference Ravani von Ow (2010) suggests 0.931 for a v/s synchronous motor (versus 0.927 using the numbers in the diagram above).



SAGMILLING.COM

2022-11-20

Vijayanagara Sri Krishnadevaraya University Bellary

How to read a motor name-plate

- Use rated power for control interlock
- Cos φ is the power factor. Motor offsets inductive loads.
- 9.02 RPM is knee point

TYPE WAZ 1500/122/76
SERIAL No. G0B031
MANUF. YEAR 2009
RATED POWER 22380 kW
VOLTAGE 5200 ±5% V
RATED CURRENT 2614.7 A
COS φ 0.97
RATED FREQUENCY 5.71 Hz
RATED/MAXIMUM SPEED 9.02/9.75 rpm
RATED EXCITATION 505 V 530 A
CONNECTION 人
INSULATING CLASS F/F
DIRECTION OF ROTATION

43

Type: WAZ 1500/122/76

Serial No. G0B031

Manuf year: 2009

Rated Power 22380 kW (mechanical output power of the motor shaft)

Voltage 5200 V

Rated current 2614.7 A (current draw at rated output power)

Cos φ 0.97 (power factor set less than zero to consume reactive power)

Rated frequency 5.71 Hz (AC power frequency at rated motor speed)

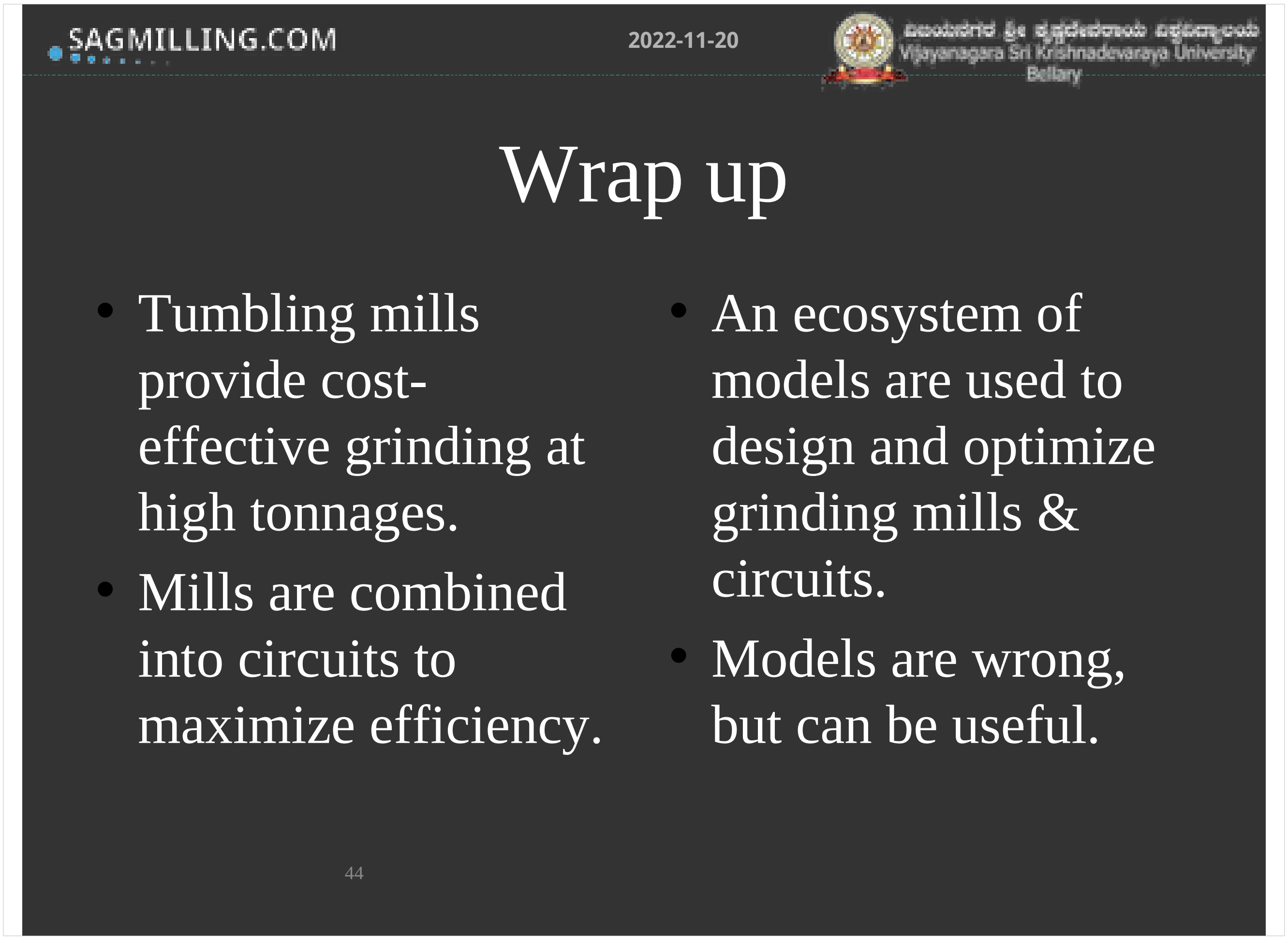
Rated/Maximum speed: 9.02 / 9.75 RPM (mill speed)

Rated excitation 505 V 530 A (power passed to the rotor circuit)

Connection Y

Insulating class F/F

Direction of rotation ∩ (can rotate in either direction)


SAGMILLING.COM

2022-11-20

Vijayanagara Sri Krishnadevaraya University
Bellary

Wrap up

- Tumbling mills provide cost-effective grinding at high tonnages.
- Mills are combined into circuits to maximize efficiency.
- An ecosystem of models are used to design and optimize grinding mills & circuits.
- Models are wrong, but can be useful.

44

Each page in this lecture could be its own short course. Don’t be concerned if you don’t follow everything right now, just soak up the buzzwords and the high level relationships between the concepts. There will be lots of time in your future mining careers to fully understand all these concepts when the time arises.

Thank you to Dr Sharath Kumar of the Department of Mineral processing VSKU Post Graduate centre in Nandihalli, Sandur Karnataka, India for the invitation to speak to VSKU.

Best wishes to all the students in your future careers.

SAGMILLING.COM

2022-11-20

Vijayanagara Sri Krishnadevaraya University
Bellary

Wrap up

https://www.linkedin.com/in/alex-doll-66b57465/

https://youtu.be/eRUgnokAYGI

45

Alex Doll, alex.doll@sagmilling.com

Follow my YouTube channel for more comminution related videos.

https://www.youtube.com/@sagmilling

Follow my postings on LinkedIn where I publish original content related to miner grinding.

https://www.linkedin.com/in/alex-doll-66b57465/

References

Alderon Iron Ore Corp. Technical Report Feasibility Study of the Rose Deposit and Resource Estimate for the Mills Lake Deposit of the Kamistiatusset (KAMI) Iron Ore Property, Labrador. *43-101 Technical Report.* December 17, 2012.

Amelunxen P., Berrios, P. and Rodriguez, E. (2014) The SAG grindability index test, *Minerals Engineering*, **55**, 42–51.

Austin, L.G. (1990). A mill power equation for SAG mills, *Minerals & Metallurgical Processing;* Society for Mining, Metallurgy & Exploration, February.

Barratt, D.J. (1979) Semi-autogenous grinding: a comparison with the conventional route, *CIM Bulletin*, (Nov) 74–80.

Barratt, D.J. (1989) An Update on Testing, Scale-up and Sizing Equipment for Autogenous and Semi-autogenous Grinding Circuits, *Proceedings of the SAG 1989 Conference*, Vancouver, Canada, Pages 25 - 46,

Bepswa, P.A., Mainza, A.N., Powell, M., Mwansa, S., Phiri, M., Chongo, C., Van Der Merwe, C., Delaney, A., Mande, P., Mulenga, D., and Batubenga, L. (2015), Insights into different operating philosophies – influence of a variable ore body on comminution circuit design and operation. *Proceedings of SAG 2015 Conference.* Vancouver, Canada, Paper № 82.

Bond, F.C. (1952). The third theory of comminution, *Trans. AIME*, **193**, 484.

Bond, F.C. (1985), *SME Mineral Processing Handbook,* **3A** 16-27.

Doll, A.G. (2013a). Technical Memorandum: SAG mill + ball mill circuit sizing, *UBC MINE331 lecture notes*, https://www.sagmilling.com/articles/12/view/?s=1 .

Doll, A.G. (2013b). A comparison of SAG mill power models, Procemin 2013, 73–84.

References

Doll, A.G. and Tischler, K. (2015). The engineering and process effects of choosing a motor design speed, Proceedings of the SAG 2015 Conference, Vancouver, Canada, Paper № 45.

Doll, A.G. (2016a). An updated data set for SAG mill power model calibration, IMPC 2016, Quebec City, Canada, Paper № 123.

Hukki, R.T. (1962). Proposal for a Solomonic Settlement Between the Theories of Von Rittinger, Kick and Bond, *Trans. AIME*, **223.** 403–408.

Morrell, S. (1996) Power draw of wet tumbling mills and its relationship to charge dynamics, *Trans IMM.* **105.** C43–C53.

Morrell, S. (2008). A method for predicting the specific energy requirement of comminution circuits and assessing their energy utilisation efficiency. *Min. Engr*. 21, 224–233

Morrell, S. (2011). The appropriateness of the transfer size in AG and SAG mill circuit design. *SAG 2011 Conference*, Vancouver, Canada, Paper № 153.

Napier-Munn, T.J., Morrell, S., Morrison, R.D., and Kojovic, T. (1996). *Mineral Comminution Circuits Their Operation and Optimisation*, JKMRC, University of Queensland, Brisbane, 413 p.

Outokumpu Mills Group (2002). *The Science of Comminution*, technical publication P. 39.