Mine-to-Mill Approach in an Underground Aggregate Operation

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Outline

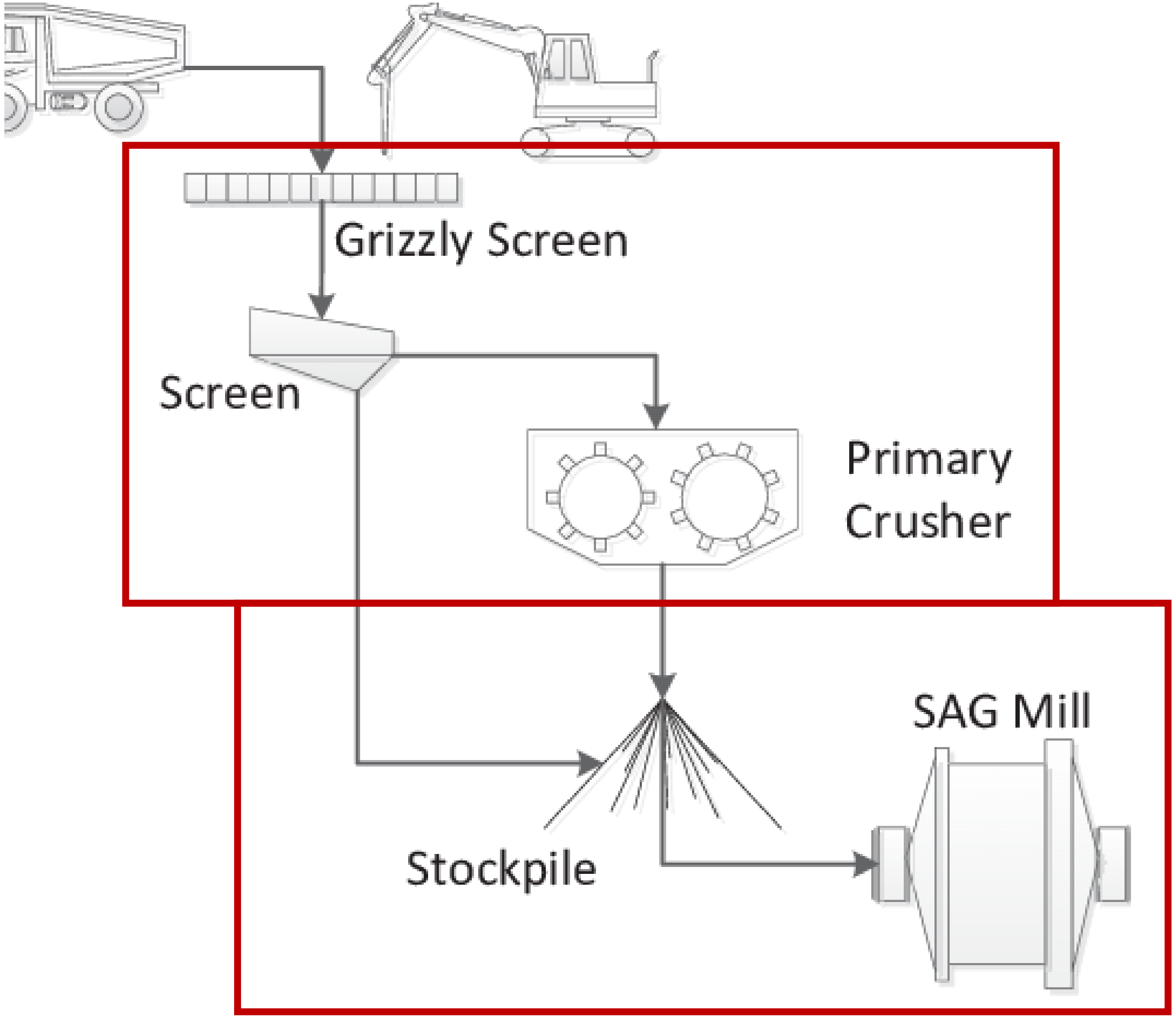
- The Mine-to-Mill Concept
- Particle Size Distribution Impact and Circuit Efficiency
- Fragmentation Models
- Energy Partition Concept
- Fragmentation Model Development
- Mine-to-Mill Strategy Implementation

The Mine-to-Mill Concept

- Strategy of communication and commitment
- Mining = series of processes
  - Performance of each individual process has upstream and downstream consequences
- Primarily focuses on optimizing blast design to achieve fragmentation with a desired particle size distribution (PSD)
  - Energy consumption in comminution process
  - Increase liberation for recovery and grade purposes
- Changing conditions in which mining occurs necessitates the need for a model that is:
  - Flexible, adaptable, & dynamic
- Most available literature and case studies deal with optimizing blast design of surface mine operations
  - Relative simplicity of surface mining
  - Powder factor can be easily correlated to downstream cost optimization

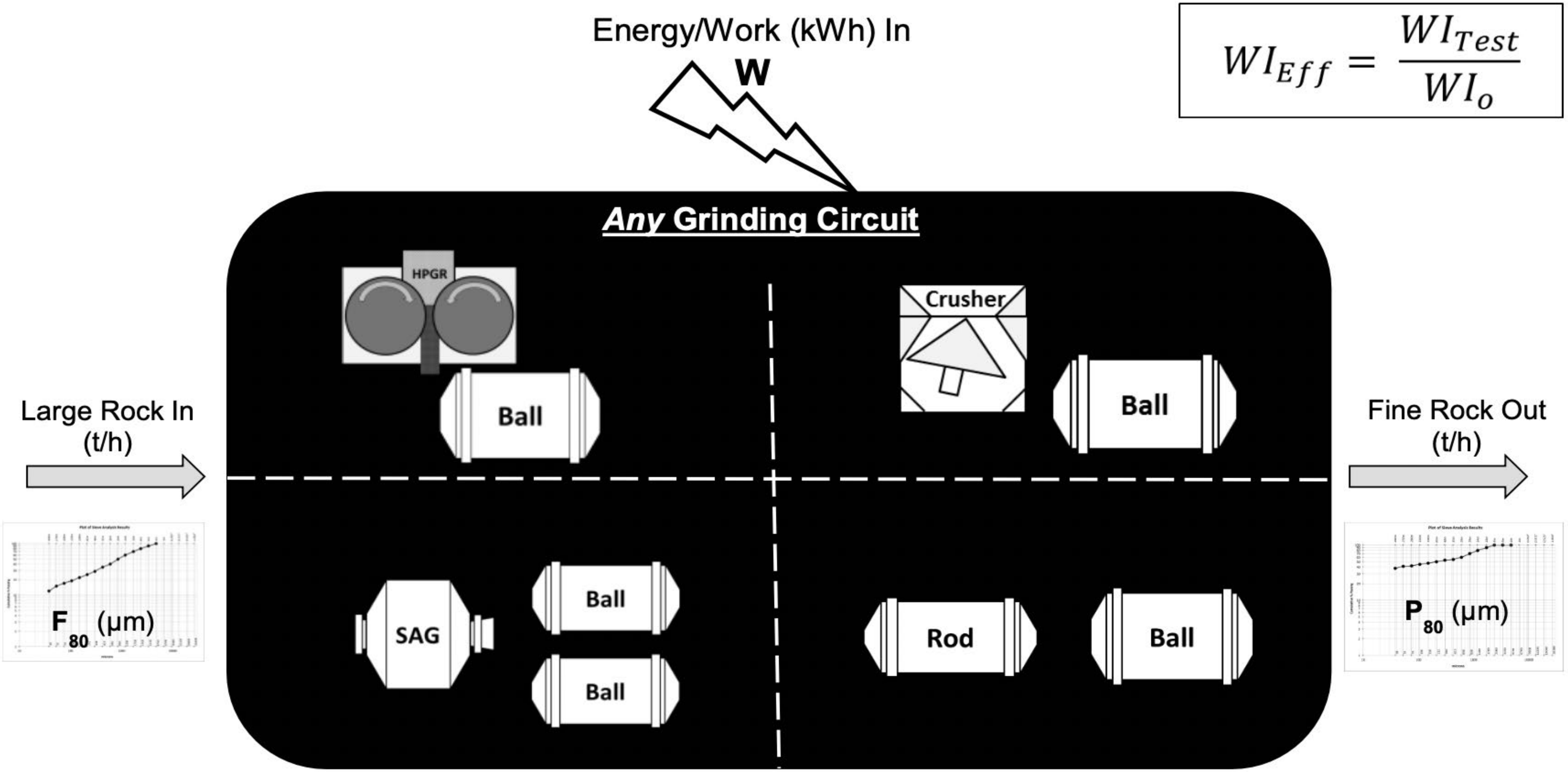
Effect of PSD on Downstream Processes

- Sieving rate decreases with increased oversize fraction
- Finer PSD results in increased throughput for first crushing stage
- Residence time is directly impacted by PSD of feed material
- Energy costs due to comminution account for ~50% of plant operating costs



Size Reduction Circuit Efficiency

$$WI_{Eff} = \frac{WI_{Test}}{WI_o}$$



$$WI_o = \frac{W}{\left[\frac{10}{\sqrt{P_{80}}} - \frac{10}{\sqrt{F_{80}}}\right]}$$

Empirical Fragmentation Models

- Most used model: Kuz-Ram
- Rosin-Rammler
- Swebrec fragmentation curve
- Julius Kruttschnitt Mineral Research Centre (JKMRC) fragmentation curve
- Kuznetsov-Cunningham-Ouchterlony (KCO) fragmentation model
- Fragmentation energy fan
- Dimensionless fragmentation model (Ouch-Sanch)

Underground Mine-to-Mill Fragmentation Models

- Decrease in discoveries of significant near surface mineral deposit
- Resulting increase in the use of underground mining methods
  - Block caving
  - Underground ring blasting
- Relationship between powder factor, fragmentation, and downstream costs is not as evident for underground mine operations
  - Confinement conditions
  - Stability of excavation
- Numerical modeling provides more accurate predictions than strictly empirical models
  - Discrete element modeling (DEM)
  - Finite element analysis (FEA)

Problems with Existing Underground Fragmentation Models

- Problems with existing models for underground fragmentation modelling:
  - Overly complex
  - Use a single point to predict a complete fragmentation size curve
  - Applicable only under specific blast conditions
  - Deterministic approach
  - Particle Size Distribution Function

Framework for Underground Fragmentation & Mine-to-Mill Model

- Any proposed fragmentation model for underground blasting applications needs to be:
  - Simple and accurate
  - Applicable over diverse range of geological and geotechnical characteristics and for a variety of underground mining methods
  - Probabilistic
  - Able to predict a range of particle size distributions
    - Model performance of an existing processing plant
    - Predict necessary design parameters of processing plant equipment needed to achieve desired final product specifications

Energy Partitioning

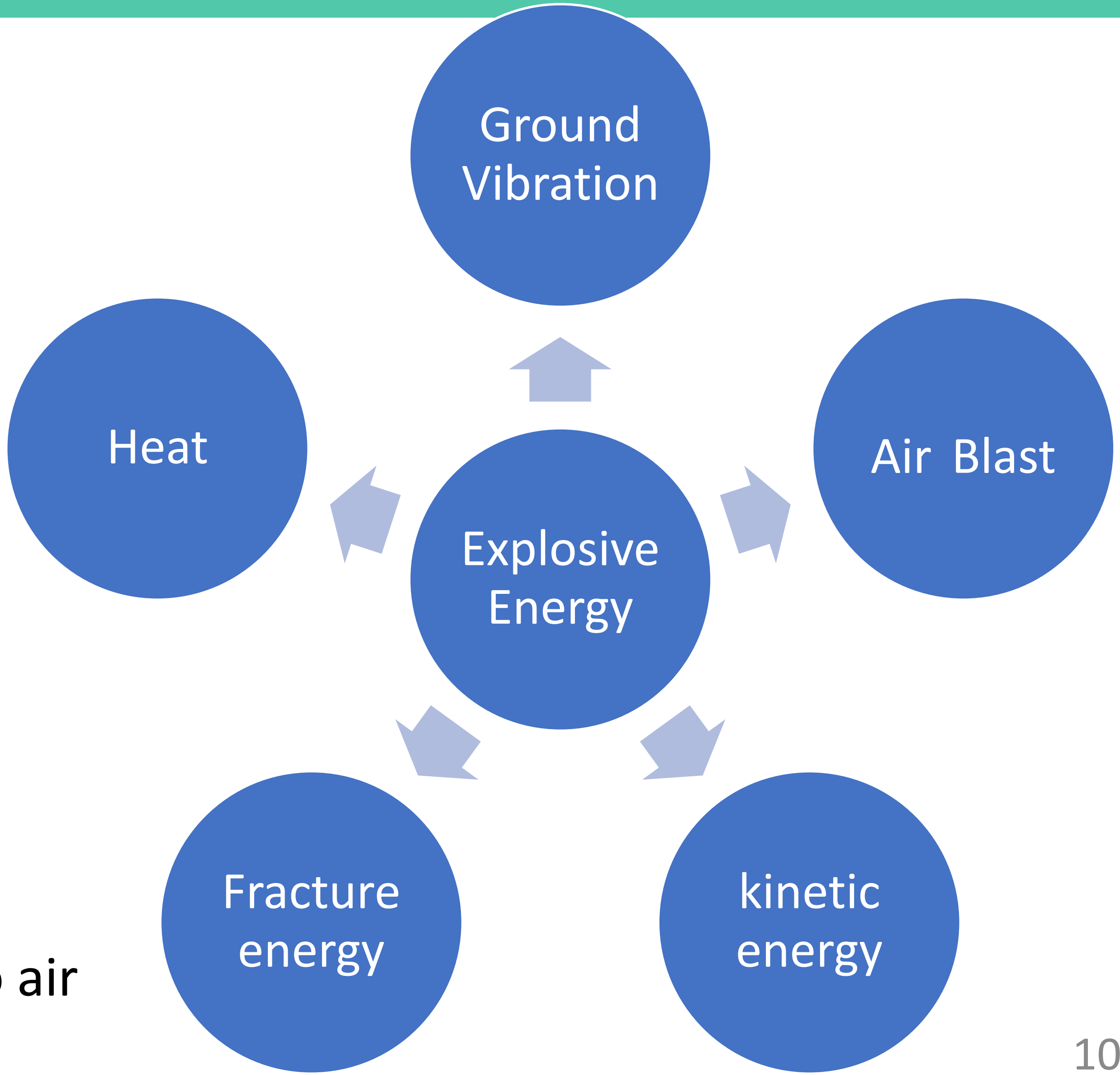
- Energy balance equation:

$$E_E = E_F + E_S + E_K + E_{NM}$$

Where:

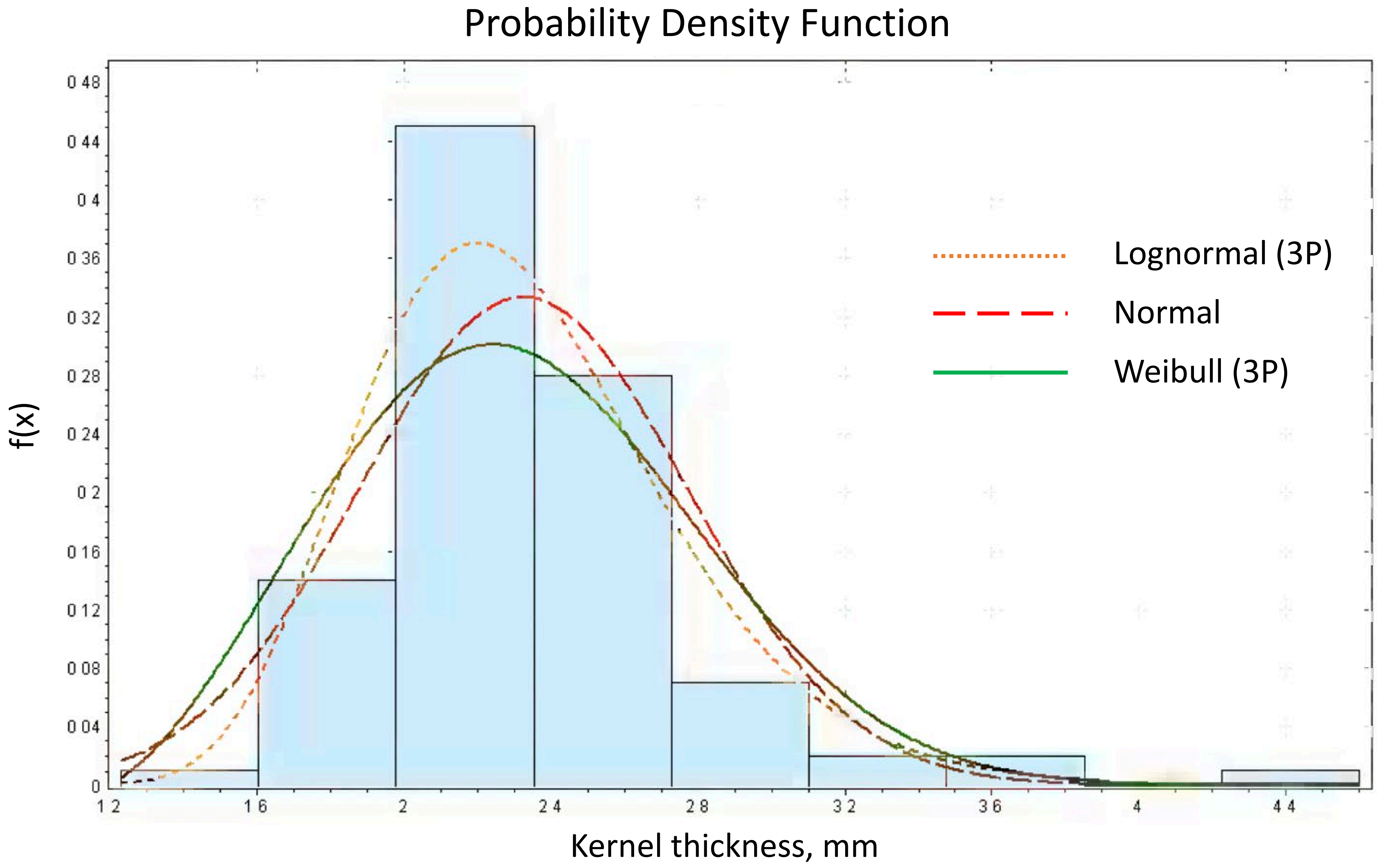
$$E_E = explosive\ energy$$
$$E_F = fragmentation\ energy$$
$$E_s = sesimic\ energy$$
$$E_k = kinetic\ energy$$
$$E_{nm} = energy\ forms\ not\ measured$$

- Maximize available explosive energy towards beneficial partition components
- Minimize available explosive energy to waste partition components
  - Minimizes risk by reducing energy going to air overblast and ground vibration



Fragmentation Model Development

- Sensitivity analysis using Monte Carlo Simulation
- Potential Variables to consider:
  - Explosive Properties
    - Explosive Density
    - Detonation velocity
    - Chapman-Jouget (C-J) pressure
  - Rock Properties
    - Young's modulus
    - Poisson's ratio
    - Uniaxial compressive strength
    - density
    - porosity
  - Blast Design
    - borehole depth
    - borehole diameter
    - borehole inclination
    - stemming
    - length
    - burden
    - spacing
    - delay timing
  - rock fabric
    - joint/fracture spacing
    - joint/fracture orientation



Histogram of the measured and predictive width distributions derived with different methods (Khazaei,, 2008)

Blast Optimization via Energy Partitioning

- Significant portion of total explosive energy can be lost to air overpressure
  - Decrease energy lost to waste partitions results in shift of energy to other partitions: heave and fragmentation

- Utilize multi-objective optimization to minimize overall operation cost (drilling cost, blasting cost, loading cost, haulage cost, and processing cost) while also reducing explosive energy transferred to airblast overpressure

- Optimization parameters will include blast design variables deemed significant when developing underground fragmentation model

Proposed Mine-to-Mill Strategy

1. The development of a blast fragmentation model for use in underground aggregate mining operations which, utilizes the log normal distribution function as an alternative to the Rosin-Rammler/Weibull distribution model, and uses a probabilistic approach rather than a deterministic approach.

2. The optimization of a blast design incorporating energy partition values as variables using multi-objective optimization.

3. The development of an underground aggregate mine-to-mill approach which incorporates the operating Work Index and Work Index Efficiency for efficiency evaluation of a size-reduction circuit.

Size Reduction Circuit Efficiency

- $W = Constant \times \left(\frac{10}{\sqrt{P_{80}}} - \frac{10}{\sqrt{F_{80}}}\right)$
  - Constant = operating Work Index = work consumed to grind ore from F80 to P80
  - Energy consumed to achieved fixed size reduction
  - Higher value means more energy is consumed to achieve same amount of fixed size reduction

- $Eff\ (WI), \% = \frac{Bond\ Work\ Index\ of\ the\ ore\ (\frac{kWh}{t})}{Operating\ Work\ Index\ of\ the\ circuit\ (\frac{kWh}{t})}$
  - Relative value and can exceed 100%
  - Value less than 100% indicates more energy being consumed to achieve same result

Simplified Algorithm for Mine-to-Mill Strategy

Simplified algorithm for mine-to-mill strategy:

- Step 1: use multi-objective optimization to determine optimum blast design parameters factoring in energy partitioning values
- Step 2: use underground blast fragmentation model to predict probabilistic range of particle size distribution caused by optimum blast design
- Step 3: determine if there is a change in energy consumption downstream in the comminution circuit of the mineral processing plant
- Step 4: based on direction of change of energy consumption either recommend proceeding with blast design or rerunning the simulations

Conclusions and Future Work

- Benefits of employing a mine-to-mill strategy are widely accepted within the mining industry
- Relationship between powder factor, fragmentation, and downstream costs is not as evident for underground mines as it is for surface mines
- Fewer available underground mine-to-mill models
- Development of new underground fragmentation model will evaluate alternatives to use of the Rosin-Rammler/Weibull distribution model
- Blast optimization will need to incorporate concept of energy partition values
- Testing of fragmentation model at additional mining operations to determine wide-range applicability

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Thank you

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