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Predicting the Effect of Particle Size and Comminution on the Extraction of Metals from E-Waste for Recycling

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Abstract : We live in a world where electronic devices are widely used in all countries. These devices utilize a wide variety of metals that require a lot of energy and processing to produce. Despite the investment of resources to produce the metals in these devices, they are commonly discarded and placed in landfills rather than recycled. Thus, much of the metal value in e-waste is not recovered, even though there are simple ways to recover metals from e-waste. Hydrometallurgical processing can be used to recover metal from e-waste, but this requires size reduction in order for it to be more effective and efficient. The effect of size is critical to reasonable hydrometallurgical extraction, yet the effect of size has not been adequately addressed. Thus, this paper discusses methods to quantify the effect of particle size and comminution on hydrometallurgical extraction of metals from e-waste.

Keywords : *E-Waste, mineral processing, Hydrometallurgy*

We live in a world where electronic devices are widely used in all countries. These devices utilize a wide variety of metals that require a lot of energy and processing to produce. Despite the investment of resources to produce the metals in these devices, they are commonly discarded and placed in landfills rather than recycled. The world generally produces about 50 million tons of e-waste each year [1]. Often, the value of the metals in e-waste is substantial with grades of materials such as copper exceeding 4 % for typical e-waste, although it can be much higher in some forms of e-waste scrap [1]. The need for elements such as copper have been increasing consistently for many years [2]. Other elements such as gold are often found in concentrations that are many times higher than in typical ores. However, much of the metal value in e-waste is not recovered, even though there are simple ways to recover metals from e-waste.

The most commonly used method for recovering metals from e-waste is smelting. The smelting process combusts the polymers in the e-waste creating carbon dioxide and consuming the material that could otherwise be recycled. Metals can also be recovered from e-waste using hydrometallurgical extraction and recovery technologies. There has been significant research effort to explore the recovery of metals from e-waste using nontraditional pathways [3-6]. However, hydrometallurgical processing requires size reduction in order for it to be more effective and efficient. The effect of size is critical to reasonable hydrometallurgical extraction, yet the effect of size has not been adequately addressed. Thus, this paper discusses methods to quantify the effect of particle size and comminution on hydrometallurgical extraction of metals from e-waste.

Figure 1 shows typical e-waste scrap that has been shredded in coarse pieces. Figure 2 shows e-waste that has been reduced to more uniformly sized particles. The metals in e-waste scrap, such as copper and gold, are

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sometimes exposed, but more often the valuable is locked inside polymer material. These particles can be treated as spheres for modeling purposes. Figure 3 shows a representation of multiple particles of inert host material, such as polymer, and valuable materials such as copper and gold. The finer the size, the more likely the valuable mineral is either liberated from the host particle matrix or partially-locked/partially-exposed as illustrated in Figure 3. Larger particles tend to have more fully locked valuable particles that are more difficult to access or inaccessible by solutions designed to extract them.

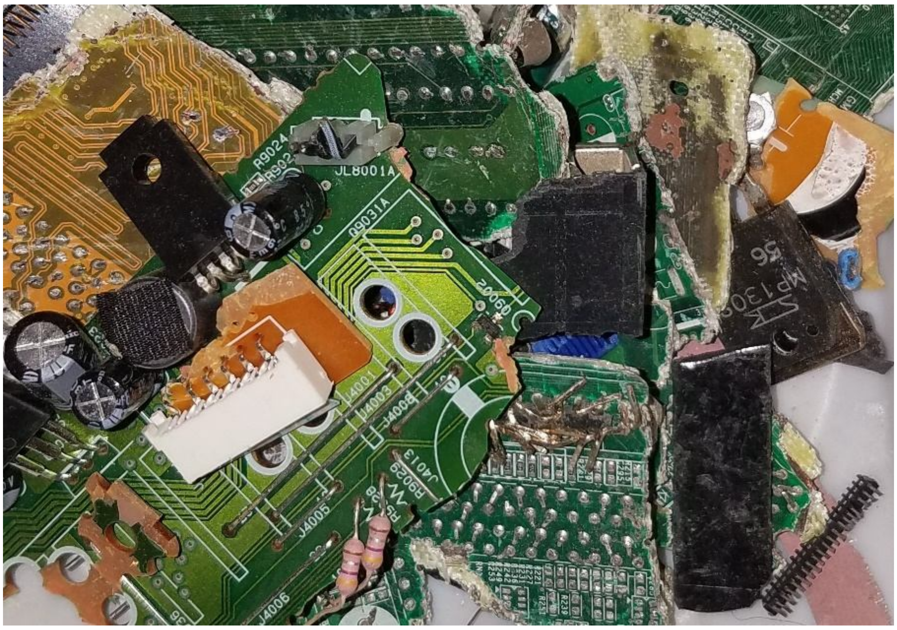

Figure 1. Picture of shredded e-waste material.

Figure 2. Shredded e-waste that has been reduced in size.

There are many opportunities to improve performance in hydrometallurgical processing of heterogeneous, metal-bearing particles, into metals. Hydrometallurgical processing often starts with leaching, which is preceded by comminution, and followed by separation and recovery. This paper discusses different techniques and modeling that can be applied to predict hydrometallurgical extraction that can also be applied to physical separations of particles.

Figure 3 provides a simple view of the relationship between a host particle (hp) and various valuable particles (vp). For typical e-waste the host material is initially much larger than the valuable particles of metal inside, but some of the valuable metal particles are likely to be liberated, some are likely to be partially exposed at the surface of host particles, and some are likely to be fully locked within the host particle matrix.

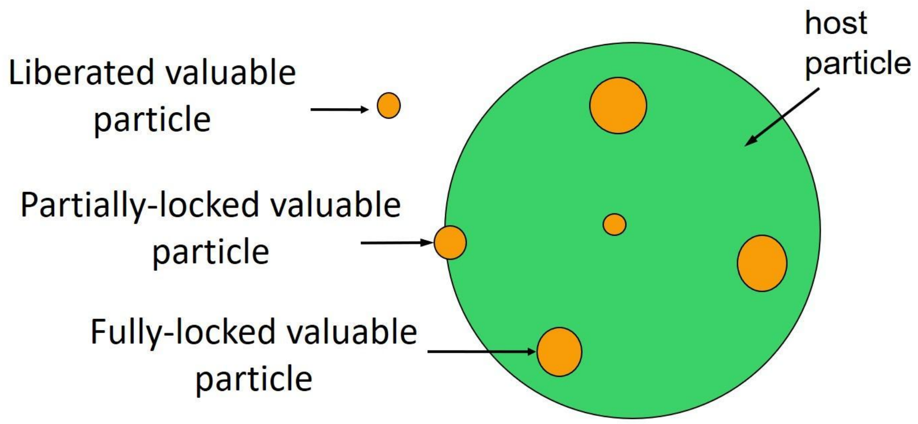

Figure 3. Schematic diagram of valuable particle liberation, partial-locking, and full-locking scenarios in relation to a host particle.

If size distributions of vp and host particle materials are compared, it is noteworthy that on the tails of the two distributions there are some host particles that are smaller than some of the valuable particles. This is important because for the segment of the particle populations where the host particle is smaller than valuable particle, the valuable particle cannot be locked inside the host particle, and it is, therefore, likely to liberated.

Using size distribution functions, this portion of the liberated valuable particle population can be calculated. Note that the probability of this liberation is related to the portion of the valuable particle distribution below a characteristic size and the portion of the host particle distribution above that size. Also, note that this characteristic size is between the two size distribution averages and can be estimated using a geometric mean. Using the Rosin-Rammler distribution function this liberated portion can be estimated using the equation [7]:

$$P_{lib.est} = exp(-(\frac{\sqrt{r_{vp}^* r_{hp}^*}}{r_{vp}^*})^{n_{vmp}})(1 - exp(-(\frac{\sqrt{r_{vp}^* r_{hp}^*}}{r_{hp}^*})^{n_{hp}})) \quad (1)$$

in which n_{vp} and n_{vp} are constants (usually between 1 and 3), r^*_{vp} is the reference radius of valuable particles, and r^*_{hp} is the reference radius of host particles. The characteristic reference radii are the sizes at which 62.3 % of the material passes as undersize. The relationship between the two parts of this equation – one for the probability of particles less than the characteristic size for the host particles and the other for the probability of particles greater than the characteristic size for the valuable particles is shown in Figure 5.

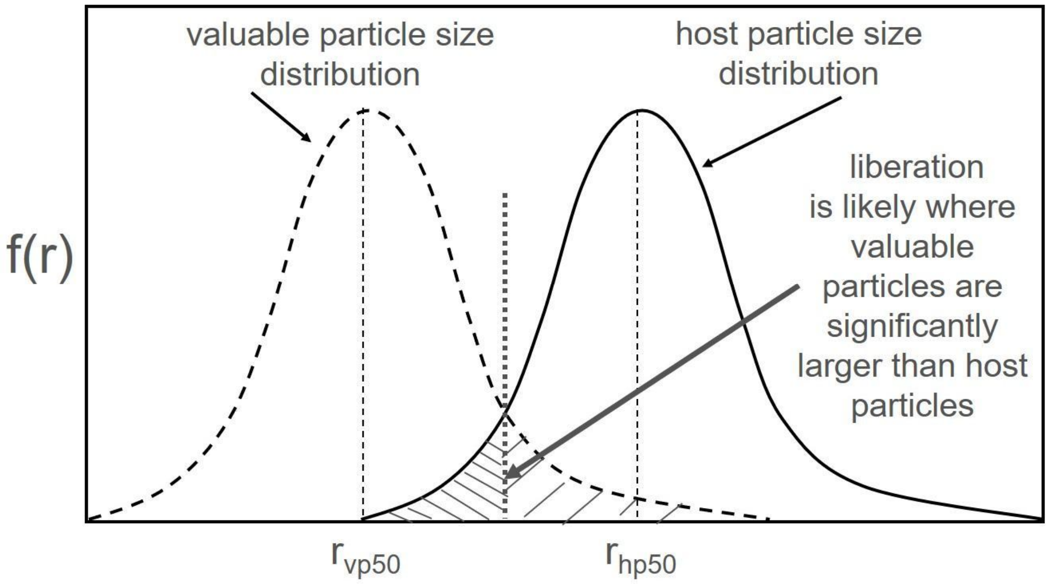

Figure 4. Comparison of typical host and valuable particle size distributions.

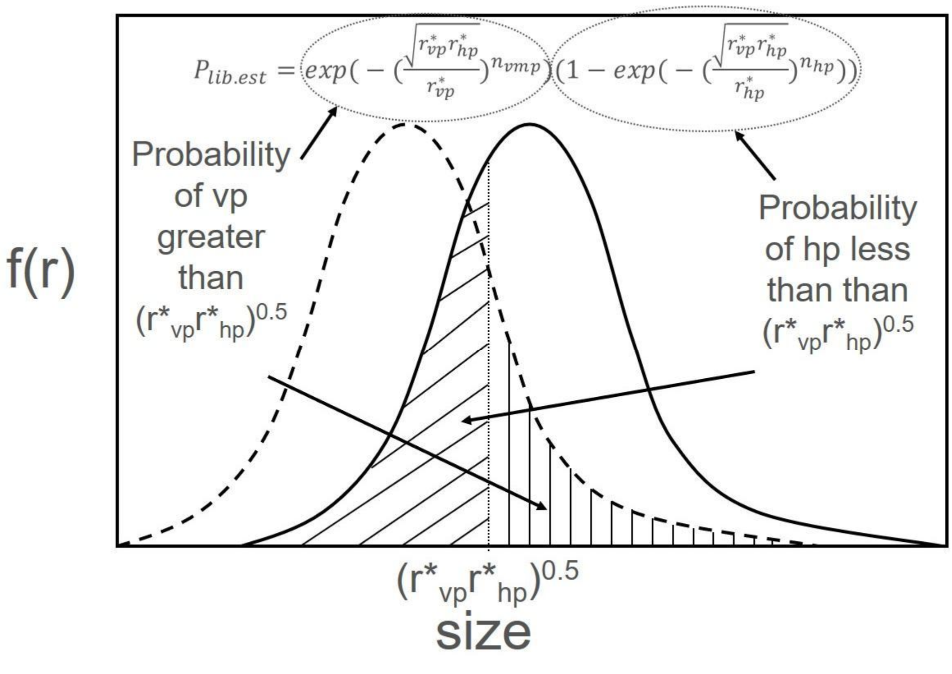

Figure 5. Comparison of typical host and valuable particle size distributions and their relationship with the characteristic size and the resulting Rosin-Rammler based probability equation for liberated particles that utilizes the probability of host particles less than the characteristic size and the probability of valuable particles greater than the characteristic size.

The probabilities of partially locked and fully locked valuable particles can be calculated using geometry and volumetric probabilities. As shown in Figure 6 the fraction of a host particle of size r_{hp} that has partially-locked or exposed valuable particles of size r_{vp} can be estimated by the fraction of the host particle volume within r_{vp} of the surface. Correspondingly, the fraction of the host particle with fully locked particles is the remainder that is not partially-locked or exposed.

The fraction of partially locked valuable mineral particles can be estimated from the nonliberated material, based on the volume of a host particle of size r_{hp} that is within the radius of r_{vp} of the surface as illustrated in Figure 6, which is calculated using the formula [7]:

$$P_{Partially-Locked.Est} = [1 - P_{Lib.Est}][1 - (\frac{r_{hp}-r_{vp}}{r^*_{hp}})^3]\ldots(for\ldots r^*_{hp} > r^*_{vp}) \quad (2)$$

The fraction of fully locked (nonexposure) valuable mineral particles can be estimated from the nonliberated material, based on the interior volume fraction of host particle of radius r_{hp} that is more than r_{vp} from the surface as shown in Figure 6, which is calculated using the formula [7]:

$$P_{Fully-Locked.Est} = [1 - P_{Lib.Est.}][(\frac{r^*_{hp}-r^*_{vp}}{r^*_{hp}})^3]\ldots(for\ldots r^*_{hp} > r^*_{vp}) \quad (3)$$

The fraction of material that is exposed to the surface through liberated and/or partial locking increases as the size of the host particle decreases in relation to the valuable mineral Particle.

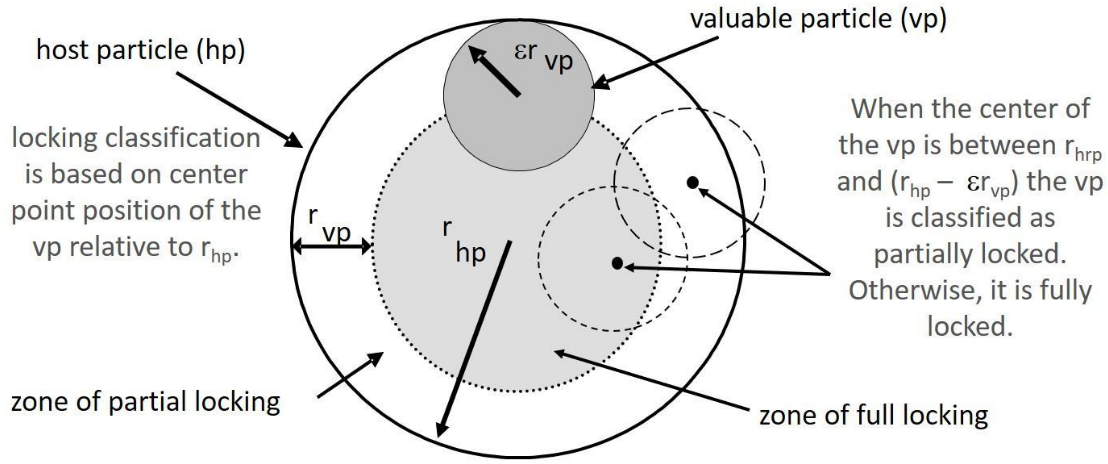

Figure 6. Comparison of positions of valuable particles relative to a host particle. The center portion is shaded to represent the zone in which the valuable particle center is too far from the outer edge to be partially locked, so it is fully locked. The zone outside of the shaded center region is the partial locking region.

Figure 7 shows how the fractions of liberated and partially locked particles change in relation to the size reduction fraction. At low size reduction factors, the partially locked fraction increases rapidly, but as size reduction continues assuming the valuable particle stays the same size, the liberated fraction continues to rise but the partial locking reaches a maximum and gradually declines as the liberated fraction continues to increase.

This approach for estimating the amount of liberated and partially locked material can be used to calculate exposure, where valuable mineral exposure is the sum of the liberated and partially locked material. The success of this method of calculating exposure relative to measured exposure data is shown in Figure 8. The data in Figure 8 show the calculations are quite close to the measured data.

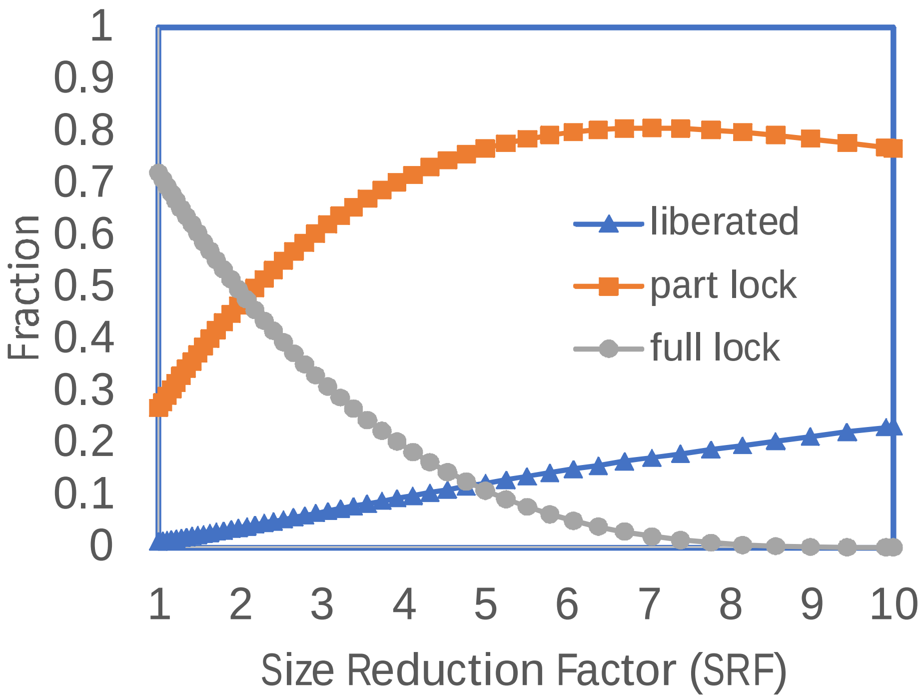

***Figure 7.** Comparison of fully locked, partially locked and liberated valuable particles as the host particle size is reduced from its original size of 1 to 10 assuming a starting valuable particle size of 0.1 relative to the host particle.*

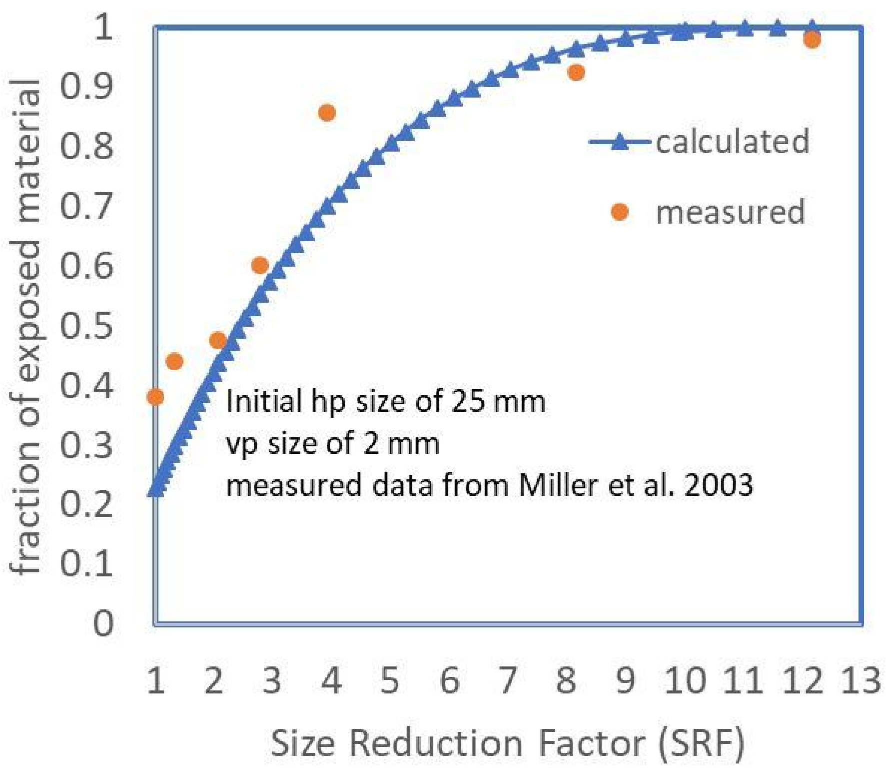

***Figure 8.** Comparison of measured exposure and exposure calculated using equations 1 and 2 as a function of host particle size reduction factor from an initial host particle (hp) size of 25 mm (SRF = 1) to 2 mm (SRF = 12.5) with a constant vp size of 2 mm using measure data from Miller et al. 2003 [8].*

Effect of host particle size reduction on valuable mineral particle size reduction

As host particles are comminuted, their size is reduced. Valuable particles inside the host particle may also be reduced in size, but the probability of VMPs being reduced is related to the size of the host particle and valuable particle. This effect can be modeled in different ways. If a spherical assessment is made in which the final particles are viewed from the perspective of where the valuable particle originated relative to the final host particle, the size reduction of the valuable particle relative to the size reduction of the host particle can be easily assessed. This approach uses the same method used for calculating partial and full locking of valuable particle in host particle. After size reduction if the final valuable particle ends up in a sphere, if it is exposed or partially locked, it can be assumed that it was broken during size reduction, likely into at least two pieces. The probability of the valuable particle ending up in the partially-exposed part of the matrix is given by the partial locking fraction of valuable mineral particles:

Sphere Model: Outer radius fracture (2 progeny) for d<D/SRF

$$P_{SMpl} = (1 - (\frac{D_{hp} - d_{vp}}{D_{hp}})^3) \quad (4)$$

The size of these particles that are fractured at the outer surface of the host particle can be assumed to be half of the original volume. Thus, the new effective particle radius for a 50 % reduction in volume is 0.794 times the original valuable mineral particle size.

The particles remaining in the interior zone after comminution can be assumed to be unfractured, and this fraction of material makes up the remainder of the material or $1 - P_{SMpl}$ relative to the outer, partially locked material. Because these particles are not fractured, their size remains at 1 times the original valuable mineral particle size. Using this approach, which multiplies the probability by the outcome size and sums two size scenarios, the relative reduction in host particle compared to the associated size reduction in the valuable particle can be calculated and plotted as shown in Figure 9. Figure 9 shows that the initial size reduction of the host particle has a very limited impact on the size reduction of the valuable mineral particle until the host particle size approaches that of the valuable mineral particle.

The same analysis can be done with a simple cube approach. For a cube, there are four categories of locations for which the final cube could have been related with a valuable particle of original size d prior to the size reduction of the host particle to size (D/SRF) as illustrated in Figure 10. These locations, superimposed from their position prior to comminution, are in the center, in which the valuable mineral particle would not be reduced in size, the side (central) in which there are 2 resulting progeny particles, the side (edge) in which there are 4 progeny particles, and the corner in which there are 8 progeny particles as represented in Figure 10. The reduction in size of the valuable mineral particle depends on the number of progeny particles. Figure 10 shows the fraction of the original valuable particle diameter (d) of sphere with equivalent volumes based on the number of progeny particles resulting from comminution associated with the interfaces shown. The probabilities of each location category are given by the probability of occurrence, which is the volume fraction of material associated with each location category using the accompanying volume fraction-based formulas:

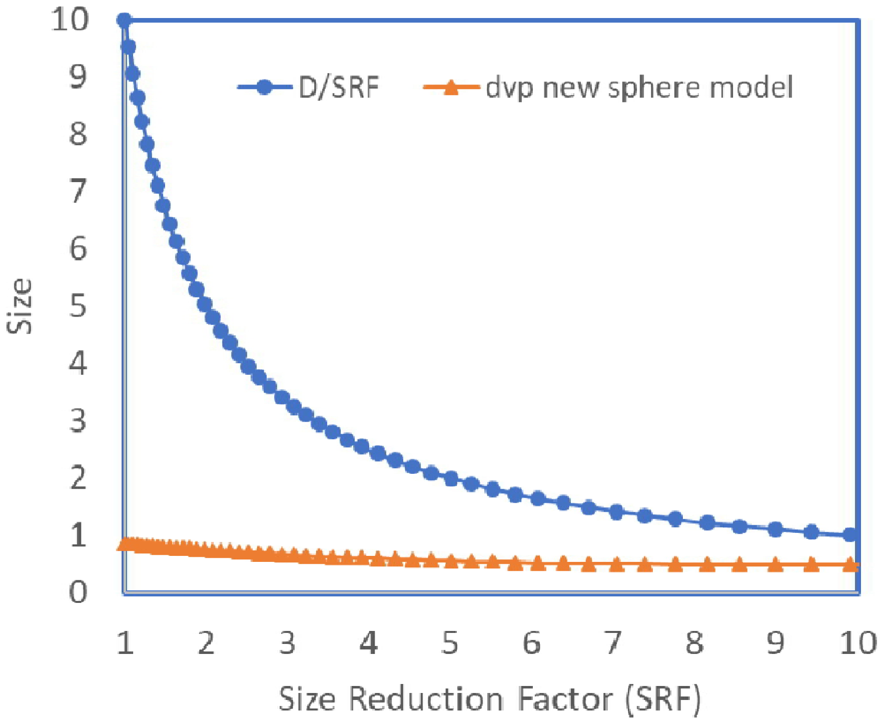

***Figure 9.** Spherical modeling of the effect of size reduction on host and valuable particles sizes based on fracture of exposed valuable particles and the use of the partial locking fraction in equation (4) to determine the probability of fracture, which is multiplied by the fractured size (0.794) and combined with the fraction of unfractured, locked valuable particle (1-P_{SMpl}) and the associated unfractured original size of 1.000. (D is the original host particle size, dvp new is the new valuable particle size after the host particle is reduced in size from D to D/SRF by the size reduction factor (SRF)).*

Cube Model probability P_{CMce}: Center (1 progeny, one basic unit site in the host particle) for d<D/SRF

$$P_{CMce} = \frac{(\frac{D}{SRF}-d)^3}{(\frac{D}{SRF})^3} \tag{5}$$

Cube Model probability P_{CMsc}: Side (Central) (2 progeny, 6 basic unit sites – one on each cube face) for d<D/SRF

$$P_{CMsc} = 6\frac{0.5d(\frac{D}{SRF}-d)^2}{(\frac{D}{SRF})^3} \tag{6}$$

Cube Model probability P_{CMse}: Side (Edge) (4 progeny, 12 basic unit sites – one for each edge) for d<D/SRF

$$P_{CMse} = 12\frac{(0.5d))^2(\frac{D}{SRF}-d)}{(\frac{D}{SRF})^3} \tag{7}$$

Cube Model probability P_{CMco}: Corner (8 progeny, 8 basic unit sites – one for each corner) for d<D/SRF

$$P_{CMco} = 8\frac{(0.5d))^3}{(\frac{D}{SRF})^3} \tag{8}$$

The sum of these probabilities is always one. The associated equivalent sphere-based sizes are determined based on the fraction of original volume in each progeny particle $(1/\text{progeny})^{1/3}$. The final size is found by multiplying the probabilities by the respective sizes and summing up the total.

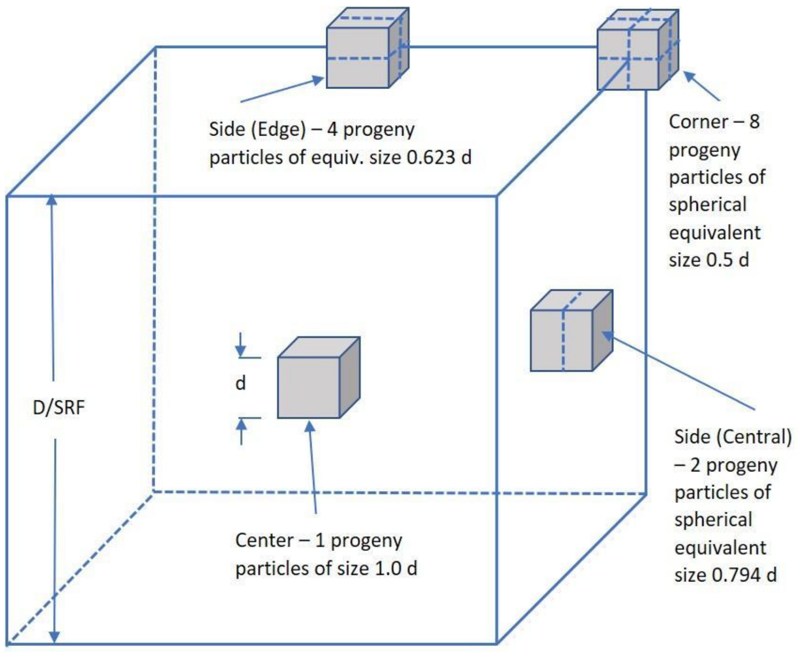

Figure 10. Schematic diagram of a cube of host particle with valuable particles in various locations. The location of the valuable particle determines the number of progeny that would be generated if the particle was at that location before comminution.

It is easy to see that when the valuable mineral particles are small relative to the host particles, it takes a lot of size reduction to significantly increase the exposure and reduce the size of the valuable mineral particles.

This approach to calculating the effect of comminution on the relative ratio of host particle size to valuable mineral particle size can be used to predict the cost of comminution relative to the impact on exposure and associated recovery of value. (Figure 11) This applies to physical separation processing recoveries such as flotation as well as to leaching recovery.

Leaching models are based on solid particle leaching and shrinking core leaching. There is also an exposed particle leaching model. Each of these models can be used in proportion to the material in the ore associated with them by utilizing the calculated fractions of valuable material in each of these categories. Correspondingly, the recoveries can be estimated from these models as a function of size reduction using these methods.

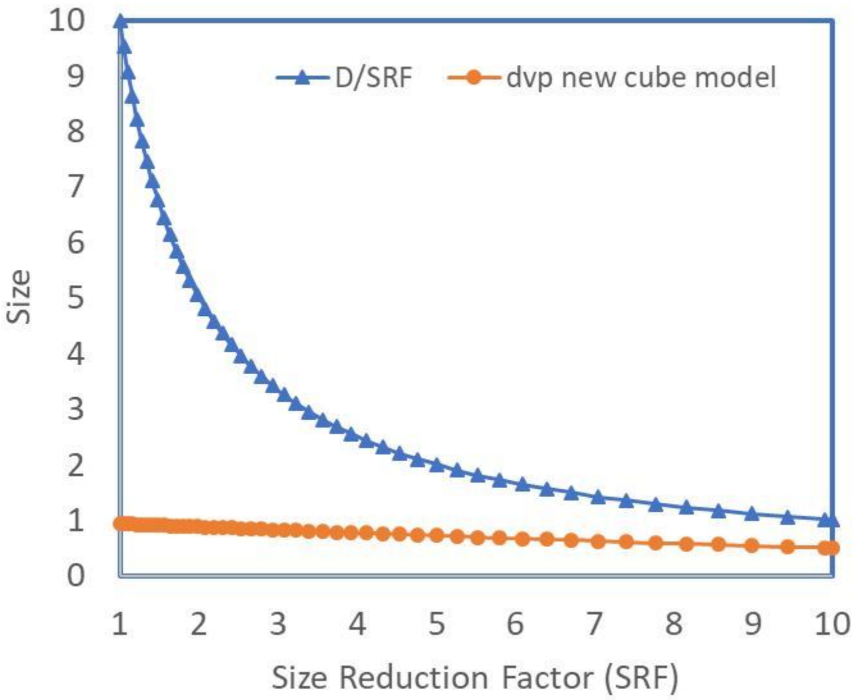

Figure 11. Cube based modeling of the effect of size reduction on host and valuable particles sizes. (D is the original host particle size, dvp new is the new valuable particle size after the host particle is reduced in size from D to D/SRF by the size reduction factor (SRF)).

The leaching kinetics can be determined using traditional leaching models that are weighted according to the fraction of material in the respective category for each model.

The time for leaching is determined using appropriate leaching models [9]. The leaching model for liberated valuable particle leaching can be estimated using the formula [10]:

k_{lib} is a reaction constant (sec/cm). is the fraction reacted. y is 1/3,1/2, or 2/3 for reaction control, rapid flow with fine particles, and slow flow with larger particles scenarios, respectively. A simplified estimate for partially-locked particle leaching can be made using the equation:

$$t(r_{vp})_{lib} = k_{lib} r_{vp}[1-(1-\alpha_{lib})^y] \quad (9)$$

Leaching kinetics for locked valuable particles are not easily determined for e-waste applications because most material locked in plastics is not very amenable to leaching through pores, although some rough estimates can be estimated using traditional shrinking-core or pore diffusion models.

$$t(r_{vp})_{Part-Lock} \approx [\frac{4\pi}{(\frac{4}{3}\pi)^{2/3}}] k_{lib} r_{vp}[1-(1-\alpha_{lib})^y] \quad (10)$$

CONCLUSIONS

Metal recovery from e-waste is an important aspect of sustainable development. The resulting metal provides an important source high value metals. The hydrometallurgical recovery of metals from e-waste is dependent on the size of the e-waste particles relative to the size of the associated valuable metal. In this paper fundamental, useful, simple methods and equations to predict the effects of size reduction on the recovery of metals from e-waste have been discussed. The methods discussed in this paper are based on simple statistics and geometries. These same methods can be applied to other applications involving heterogeneous materials for which size reduction is needed for commercial chemical extraction or physical separation.

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