Chapter 8
Comparative Advantages of the Mineral Processing of Deep-Sea Polymetallic Nodules over Terrestrial Ores

Chris Duhayon and Simon Boel

Abstract A review of comparative advantages of mineral processing of deep-sea polymetallic nodules over terrestrial ores is attempted. The work conducted as part of Global Sea Mineral Resources' onshore processing development strategy has contributed to answer the critical questions related to the choice of the flow sheet, the adequateness of the beneficiation of polymetallic nodules, the behavior of nodules with regard to comminution, and how it compares to land-based ores in terms of energy intensity. The results suggest there is an undisputable environmental advantage associated with the comminution of polymetallic nodules as compared to conventional (monometallic) land-based ores, due to their higher grade, polymetallic character, and comminution behavior.

Keywords Polymetallic nodules · Mineral processing · Beneficiation · Comminution · Metal-specific energy · Manganese · Nickel · Copper · Cobalt

1 Introduction

This chapter proposes a view of the comparative advantages of mineral processing of deep-sea polymetallic nodules over terrestrial ores. As Global Sea Mineral Resources (GSR) incorporated the onshore processing of nodules in its development strategy, critical questions related to mineral processing were raised: What should the process flow-sheet look like? Is the beneficiation of polymetallic nodules to be ruled out upfront? What is the comminution behavior of nodules, and how does it compare to land-based ores? Is there a gain in energy intensity related to the mineral processing of nodules compared to terrestrial ores, and if so, what are the drivers? As the work progressed toward finding an answer to these questions,

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advantages started to emerge, which required to be formalized and put into perspective. The present work is a contribution to that purpose.

The first part provides a brief reminder on the deep-sea polymetallic nodules characteristics that are relevant to our discussion. A short review on the manganese ore beneficiation processes is then proposed and used in a discussion about their restricted application to polymetallic nodules. This is put into perspective in the light of the results of a nodules sample preparation, which concludes this part.

The second part briefly reviews the literature treating comminution characteristics of polymetallic nodules and shares chosen data from a study on the grindability of the polymetallic nodules. The results of the Bond Ball Mill Work Index and Abrasion Index test-work are discussed and compared with land-based ores. Useful considerations related to comminution equipment wear rates are shown. It concludes by showing the results of a comparison of metal-specific energy, a metrics that take the grade and the polymetallic character of ore into account when comparing the comminution energy intensity.

2 Polymetallic Nodules Beneficiation

2.1 Deep-Sea Polymetallic Nodules Characteristics

Deep-sea polymetallic nodules and their physicochemical characteristics have been exhaustively studied in the past, (Burns and Fuerstenau 1966; Barnes 1967; Fuerstenau and Han 1977, 1983; Mukherjee et al. 2004; Wang et al. 2009; Hesse and Schacht 2011; Dreiseitl and Bednarek 2011; Kuhn et al. 2017). This section refreshes the necessary aspects for the following discussion and presents results from a study carried out for GSR by a specialized partner.

In their seminal work, Burns and Fuerstenau (1966) observed the manganese phase as δ-MnO_2, 7 Å manganite and 10 Å manganite, and an iron-rich amorphous phase believed to contain hydrated FeOOH. Nickel, copper, magnesium, aluminum, and potassium are deported in the manganese phase, and cobalt, titanium, calcium, and silicon are deported in the iron phase (Burns and Fuerstenau 1966). The manganese oxides were later identified as birnessite, todorokite, s-birnessite (Giovanoli et al. 1970), hydrohausmanite, and vernadite (Post 1999). Fuerstenau et al. note that nodules consist of 100 Å–500 Å colloidal particles as evidenced by the internal pore size distribution and by the electron probe and scanning electron microscopy studies (Fuerstenau and Han 1977, 1983). The nodule samples mentioned in their work originate from the Mexican coast, Polynesia, and one from the UKSR contract zone, and the gangue characteristics are not discussed in detail. It is therefore arguable that the presented results would be valid for nodules originating from other parts of the CCFZ.

In terms of species deportment, the results obtained by our specialized partner are in agreement with previous observations (Burns and Fuerstenau 1966; Fuerstenau and Han 1983) and indicate that manganese is unevenly deported in the manganese-rich and iron-rich phases, cobalt is only present in the iron-rich phase and nickel and copper are mainly present in the manganese-rich phase. No deportment of metal of interest (Ni, Co, and Cu) is observed in the gangue. The gangue represents 30% by weight of the dry nodules and has been observed as free grains and fine inclusions in the manganese and iron phases, with d_{50} of 16 μm for the quartz, 17 μm for the feldspars, and 21 μm for the micas present in the manganese-rich phase but also in a smaller proportion (<20%) in the iron-rich phase. The CCFZ polymetallic nodules bear some similarities with the terrestrial manganese oxide ores as they are in the oxidized form and with their manganese grade of 30% wt. and iron grade around 5% wt., their Mn/Fe ratio is around 6, which is much lower than 11.3, an Mn/Fe average based on a sample of low-, medium-, and high-grade ores from diverse origins (South Africa, Australia, West Africa, Latin America, Eastern Europe, and India), and also lower than 8.8, an Mn/Fe average based on a subset sample of high-grade ores (grades > 40% wt.) from the previous sample.

2.2 Presentation of the Manganese Oxide Ore Beneficiation Processes

As the beneficiation options for polymetallic nodules are discussed, it is adequate to mention the processes applied to manganese ores: the low and medium grade manganese ores are usually upgraded by beneficiation processes, which after crushing and screening would include jigging, spirals, dense media separation, flotation, or a combination thereof (Singh et al. 2019). The choice of the beneficiation process depends on the nature of the ore (siliceous, carbonate, or oxide). For the oxide ores, the goal is not only to upgrade the ore but also to ensure an adequate Mn/Fe ratio, as the ferruginous ores with an Mn/Fe ratio lower than 1.5 are not suitable for metallurgical processing. The main manganese oxide ore beneficiation plants such as those found in GEMCO in Australia (Groote Eylandt Mining Company, part of the South 32 group) and COMILOG in Gabon (part of the Eramet group) use gravity separation methods, such as dense media techniques and jigging (Singh et al. 2019).

The specific gravity of iron-bearing impurities in these ores varies between 4 and 5.2, whereas the manganese oxide minerals have a specific gravity higher than 4, which complicates the gravity separation process (Singh et al. 2019). The gangue minerals such as quartz, gibbsite, and kaolinite have a lower density and can therefore be removed by gravity separation, in which case the upgraded mineral flow will still contain manganese and iron species.

Magnetic separation is another method used to sort the ores. It is based on their magnetic properties such as permeability and susceptibility. Ores containing ferromagnetic minerals (e.g., magnetite) can be separated or enriched with low-intensity magnetic separators, while paramagnetic or weakly magnetic particles require higher flux densities found in high-intensity magnetic separators, typically ten times those of low-intensity magnetic separators (Fuerstenau and Han 2003). However, the paramagnetic iron minerals such as hematite and goethite offer only a narrow difference in magnetic properties from the also paramagnetic manganese minerals (Gao et al. 2019). In the latter case, a solution to circumvent the limited success of the habitual magnetic separation process is to perform a preliminary reduction roasting. The reduction of the paramagnetic hematite to ferromagnetic magnetite widens the difference in magnetic susceptibility and allows an efficient magnetic separation. An increase of manganese grades from 36% wt. to 44% wt. with limited loss of manganese and increase in Mn/Fe (Gao et al. 2012), and an increase of manganese grades from 30% wt. to 56% wt. with a 71% recovery yield of manganese and an increase in Mn/Fe from 1.04 to 10.85 (Gao et al. 2019) have been reported.

Flotation has previously been studied in the context of manganese oxide ore beneficiation (Fuerstenau et al. 1986). It is generally observed that flotation of oxide minerals can upgrade the ore by removal of gangue minerals (Mehdilo and Irannajad 2014; Rahimi et al. 2017), but the selective separation of manganese and iron is poor (Bayat et al. 2013; Singh et al. 2019). One of the reasons is the ambiguity of the ranges of point of zero charge of hematite (pH 4.0–8.9) and pyrolusite (pH 4.2–7.4), which seem to be highly dependent on the origin of the mineral (Parrent 2012). The consequence is a limited increase in the Mn/Fe ratio by flotation itself.

2.3 Discussion of the Beneficiation Processes for Polymetallic Nodules

Although both the Mn grade and the Mn/Fe ratio of polymetallic nodules would suggest the benefit of upgrading them, the dissemination of metals of interest and their intricate structure question both the possibility and the attractiveness of beneficiation: the mineralized fraction represents the major part of the ore and the metals of interest are deported and finely disseminated in the manganese and iron-bearing phases; the gangue particle sizes and the particle density differences are at the lower end of the size range of common size-separating and gravity-separating devices, except in special circumstances (Fuerstenau and Han 2003). Preconcentration of deep-sea polymetallic nodules via density separation, flotation, and magnetic separation is commonly considered to be impossible (Wegorzewski 2018).

It is known that separation by density difference under gravity becomes less efficient for fine particle sizes, and that flotation becomes the dominant separation process with this regard (Gupta and Yan 2016). However, gravity separation usually exhibits advantages over flotation: a lower installed cost and power requirement per ton of throughput, and the absence or reduction of expensive organic reagents. Two main methods can be used to evaluate the effectiveness of gravity separation: the evaluation of the ±0.1 specific gravity, and the calculation of the equal settling ratio (Fuerstenau and Han 2003; Gupta and Yan 2016). Depending on the methods to be

Table 8.1 Densities of manganese/iron mineral and gangue species

	Species	Density (–)
Manganese/iron minerals	Vernadite	2.9–3.0
	Birnessite	3.0
Gangue	Quartz	2.7
	Albite	2.6
	Mica	2.8–3.0
	Feldspath	2.6–2.8

used, the determination of the respective densities of the species to be separated and a sink-float analysis are recommended. As shown in Table 8.1, the manganese/iron mineral species and the gangue species have similar densities. The gangue density was estimated at 2.7 by using its weight composition and the density of its mineral components.

Heavy media separation would require the use of a solid heavier than the mineral to be floated to produce a quasi-stable suspension which density is intermediate between the manganese-rich phases (density range: 2.9–3.0) and the gangue (density 2.7). Heavy media vessels can handle tonnages as high as 700–800 tph, however with coarse material (Fuerstenau and Han 2003). Instead of carrying out a sink-float analysis on nodules crushed and ground to #100, a preliminary evaluation of the criteria used by the two methods was performed. An ideal scenario was assumed by considering that the gangue particles and the Mn-rich particles are perfectly liberated and have respective densities of 2.7 and 2.9. These assumptions lead to the hypothetical sink-float test data shown in Table 8.2. They clearly illustrate the difficulty to find an adequate heavy liquid for a sink-float separation. Tribromomethane (density of 2.87) would be a candidate but is a Group 3 carcinogen and linked to liver toxicity (Gupta and Yan 2016), so a pseudo heavy liquid with adequate density could be used. The case is too simplified to represent washability curves inferred from the data in Table 8.2, but the examination of the ±0.1 specific gravity distribution shows values higher than 25, which is considered as a threshold value for gravity separation feasibility (Gupta and Yan 2016). The hypothesis of an ideal scenario is not restrictive in our case, as a distribution of particles composed of gangue and Mn-rich minerals would always exhibit ±0.1 specific gravity values higher than the ideal case represented in Table 8.2. It can be concluded that the implementation of the sink-float separation method for polymetallic nodules is impossible in the current technological context.

In the same conditions, the equal settling ratio $^{d_L}\!/_{d_H}$ (also known as the concentration criterion) was evaluated using Eq. (8.1) for the manganese mineral species (vernadite, birnessite) and the gangue, considering water as the fluid used for separation. In Eq. (8.1), ρ_H is the specific gravity of heavy particles, ρ_L is the specific gravity of light particles, ρ' is the apparent specific gravity of the fluid or the suspension (in case of hindered settling), and the exponent n depends on the regime (Newtonian or Stokesian).

Table 8.2 Hypothetical sink-float test data related to the ideal situation involving perfectly liberated gangue particles (30 wt%) and Mn-rich particles (70 wt%) with respective specific gravities of 2.7 and 2.9

Specific gravity range	Mass (wt%)	Cumulative float mass (%)	Cumulative sink mass (%)	±0.1 Specific gravity distribution
F2.7	0	0	100	–
S2.7–F2.8	30	30	100	30
S2.8–F2.9	0	30	70	70
S2.9–F3.0	70	100	70	70
S3.0	0	100	0	–

$$d_L / d_H = \frac{(\rho_H - \rho')^n}{(\rho_L - \rho')^n} \quad (8.1)$$

Three sets of assumptions considered as limiting cases were used:

(a) Free settling, the solids concentration in water being neglected ($\rho' = 1$ g/cm^3) and Newtonian conditions ($n = 1$).
(b) Hindered settling, 25% solids in water ($\rho' = 1.45$ g/cm^3) and Newtonian conditions ($n = 1$).
(c) Hindered settling, 50% solids in water ($\rho' = 1.65$ g/cm^3) and Stokesian conditions ($n = 0.5$), which seems realistic for a slurry containing fine particles.

The range of values of the equal settling ratio obtained is 1.1–1.2 in all three cases, which indicates an almost impossible separation at any size as the range is lower than the threshold value of 1.25 (Gupta and Yan 2016). In this range of values, however, it is suggested that flotation films or flowing films concentrators could be implemented (Fuerstenau and Han 2003).

Flowing film concentrators, like the tilting frame and the spiral concentrator, use the differential speed of particles in a thin film of water and fine particles going down a slightly inclined plane. As the technique requires a large flowing film surface area, its development is aimed at decreasing its footprint (Fuerstenau and Han 2003). With a usual capacity of 1 t/day/m^2, the footprint of a tilting frame for a 375 tph dry nodules would be in the order of magnitude 9000 m^2, which is clearly impracticable. While the implementation of a tilting frame is not impossible, the previous considerations question the size and economics of the equipment that would be used for a polymetallic nodules commercial operation.

On the other hand, the option of a spiral separator seems more viable for throughput of 3×10^6 ton of dry polymetallic nodules per year. Considering 12-spiral modules of triple-start spirals (Gupta and Yan 2016) including a rougher, a scavenger, and a cleaner at a 3 tph feed rate per spiral, a feed size range of 45–850 µm and a 16 m^2 footprint for each module, 32 modules would be required. A total footprint of the spiral concentrators of 2800 m^2 is then calculated following habitual rules used to evaluate the footprint of industrial facilities (Caceres et al. 2020). This value is high but more in line with current industrial practice and could mandate further investigation of the application of spiral separator in combination with other screening methods for polymetallic nodules.

As mentioned in the previous section, magnetic separation methods have been applied to low-grade manganese ores, optionally with a preliminary reduction roasting step. This mineral processing route was not investigated, but recent attempts based on earlier work (Leonhardt 1979) have shown the interest in pursuing this option. The preliminary reduction roasting step is crucial in the process, as the small particle size, the heterogeneous distribution of the metals in the nodules, and the fact that the different Mn–Fe (oxy) hydroxides are epitaxially intergrown with each other, make a direct magnetic separation process impossible (Wegorzewski 2018). The reduction roasting step was tested with some success with the addition of coke, quartz, and elementary sulfur to a rotary kiln at 1050–1100 °C for 2 h. This produced metal-rich particles with a D90 < 12.71 μm, which is too small for usual beneficiation methods. These metal-rich particles contain Fe, Ni, and Cu. Other phases are present as well, that is, MnS, and a slag of Mn-oxide and Mn-silicates (Wegorzewski 2018). Another attempt used nodules from the China Ocean Sample Repository and the addition of anthracite, quartz, calcium fluoride, and iron sulfide (II) to a crucible in a muffle furnace at 1100 °C for 0.5–4 h (Zhao et al. 2020). The metals of interest (copper, nickel, and cobalt), as well as iron, were reduced to their metallic form in a magnetic phase, while a small fraction of the manganese was reduced to the metal. The obtained particle sizes were D90 < 100 μm, which allowed a magnetic separation step to follow. The overall recoveries were around 80–85% for nickel, copper, cobalt, 91% for iron, and 5.6% for manganese. The Mn/Fe ratio in the nonmagnetic phases was not mentioned as manganese is mainly present in three different phases (ferromanganese sulfide phase, manganese olivine phase, and a glass phase), but the prevalent glass phase seems to have an Mn/Fe ratio of 4.7 based on the SEM imagery and the electron-probe analysis, while the initial Mn/Fe ratio of the nodules is 4.1. This questions the prospect of the downstream valorization of the manganese in this process and suggests a three-metal business case (i.e. excluding the valorization of manganese in the flow-sheet).

With regard to flotation, it is known that the technique is not efficient for metal beneficiation when applied to nonchemically processed nodules (Fuerstenau and Han 1983; Wegorzewski 2018). No application to polymetallic nodules seems to have been investigated, although the flotation of manganese carbonate from the Cuprion ammoniacal leach tailings has been evoked (Haynes 1985). It can also be applied to nodules which have undergone the reduction roasting process previously mentioned, in which case it has been found that the flotation of the product from the reduction roasting with a sulfur addition higher than 2% in weight leads to higher metal recoveries than the magnetic separation, probably due to the formation of easily floated sulfides (Sridhar 1974). The segregation process (using coke and chloride salts) has also been reported to allow for a downstream flotation (Fuerstenau and Han 1977).

However, a desliming test work was recently subcontracted to a specialized partner. The desliming step was carried out with a Mozley hydrocyclone kit as a basis for a custom-built apparatus and took place after crushing and grinding polymetallic nodules to #100 (P80 148 μm). Qualitative mineralogical observations were made before and after the desliming test with a Zeiss binocular microscope under reflected light. They showed that the feed contained a lot of agglomerated fines identified as clays and micas. Following the hydrocyclone separation, a major fraction of the micas and clay minerals seem to have been removed under the optimal condition test work, which is the one producing a P80 181 μm for the underflow of the hydrocyclone. The XRF and ICP analysis of metals of interest in the feed and the product showed a limited upgrade ratio of 1.15. The results of this test work suggest that the crushing and grinding process preferentially liberates gangue in the fine particles, which confirms a previous similar observation (Yoon et al. 2015). This suggests that a size classification with the purpose of desliming is possible, and even recommendable for further hydrometallurgical processing.

To summarize, it has been shown that the beneficiation of deep-sea polymetallic nodules is challenging but not impossible. There is evidence that reduction roasting preceding a separation process such as flotation or magnetic separation could be implemented in the future, most probably for the three-metal business case. On the other hand, even if the gangue particle sizes and the particle density differences are at the lower end of the size range of common size-separating and gravity-separating devices, there is an advantage in studying further the size classification (with hydrocyclones) or gravity separation (with spiral concentrators) opportunities for polymetallic nodules, as a four-metal processing option can benefit from a desliming and improve the feed upgrade for the hydrometallurgical operations.

3 Polymetallic Nodules Comminution

3.1 Introduction

The comminution of polymetallic nodules is not well covered by literature. It is generally assumed that the nodules would be crushed and milled before any metallurgical processing (Fuerstenau and Han 1977). Among the parameters related to comminution, the Bond Ball Mill Work Index BWi is a convenient way to report the grindability of the ore and has been widely used for equipment design (Fuerstenau and Han 2003; Wills and Napier-Munn 2006). While the values of the Bond Work Indices are fairly documented for terrestrial ores, it is not the case for polymetallic nodules. Fuerstenau and Han (1977) noted that in the case of processing of soft nodules, the size reduction may be carried out simply in hammer mills and that energy consumption for size reduction in nodule processing should not be large. The only values reported are mentioned in Table 8.3 (Brooke and Prosser 1969).

The values reported for the Bond Work Indices (BWi) show a high variability depending on the geographical origin of the nodules, which can be correlated to their composition, structure, and formation mechanism. These aspects have been already exhaustively discussed (Kuhn et al. 2017). Except for the values of the Bond

Table 8.3 Bond ball mill work indices and sampling location of polymetallic nodules (Brooke and Prosser 1969)

Sample reference	BWi (kWh/t)	Coordinates and depth	Approximate location
2P-52	13.7	9°57'N, 137°47'W, 4930 m	UKSR CCFZ exploration zone
2P-50	7.7	13°53'S, 150°35'W, 3623 m	French Polynesia EEZ
DH-2	8.8	21°50'N, 115°12'W, 3430 m	Mexican EEZ
Average	**10.1**		

Ball Mill Index BWi 9.4 kWh/t and the Abrasion Index Ai 0.0047 g reported by Deep Green in its technical report (DeWolfe and Ling 2018), no data have been found in relation to the Bond Low Energy Work Index, the Rod Mill Grindability Work Index, or the abrasion characteristics of the nodules in the context of the comminution operations.

The lack of information on the nodule's comminution prompted GSR to de-risk the development of the comminution operations. With that regard, a study on the grindability of the polymetallic nodules was commissioned to a specialized partner. The sample used for the study was combined from subsamples obtained by GSR during successive cruises in its exploration contract area in the CCFZ.

3.2 Results of the Investigation of the Grindability of the CCFZ Polymetallic Nodules

The panel of tests included among others: a determination of the PSD of the sample, an SMC test (SAG Mill Comminution), a Bond Low Energy Impact test (CWi), a Bond Rod Mill Grindability test (RWi), a Bond Ball Mill Grindability test (BWi), and a Bond Abrasion test (Ai). The test work allowed the assessment of the comminution parameters of the polymetallic nodules and confirmed the energy requirements, and established the SAB flow sheet (semiautogenous/ball mill) as the optimum comminution circuit preceding the metallurgical process (using the JKSimMet software and Bond's third theory of comminution). The particle size distribution of the nodule feed is presented in Fig. 8.1.

The Bond Low Energy Impact test is used to evaluate the power requirements for crusher sizing. The test returned a CWi work index of 0.5 kWh/t,[1] which is very soft, and no crusher is considered in the circuit. The sample is very soft at coarse and moderate grinding sizes (Rod Mill Work index RWi 6.5 kWh/t[1], SPI 10.4 min), and soft at finer grindability sizes with a BWi 10.1 kWh/t[1], which is incidentally equal to the average of BWi reported in Table 8.3. The comparison of the Rod Mill Work index with the Ball Mill Work index confirms the intuition that the ore is indeed very soft but hardens with size reduction, a trend that may be reconciled with the

[1] For the comminution results, masses are expressed in short tons. We use "metric ton" when necessary to show the difference.

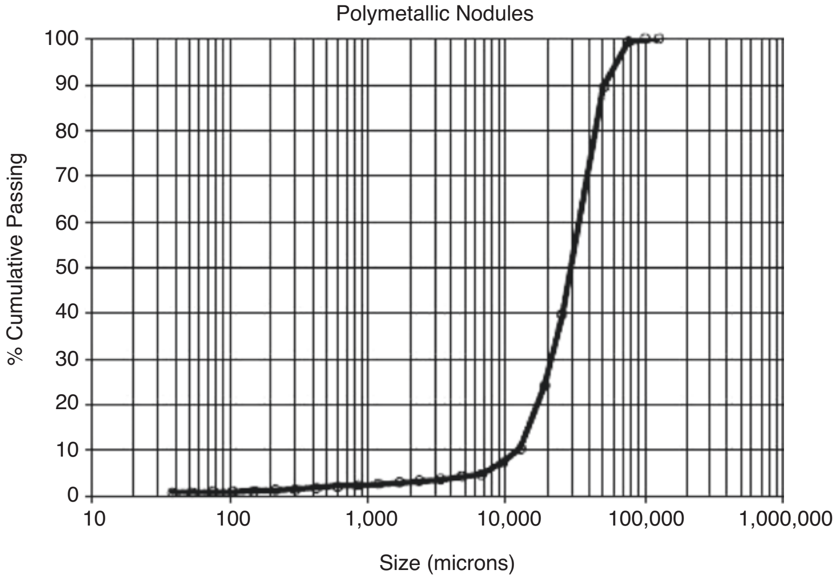

Fig. 8.1 Particle size distribution of the GSR CCFZ nodule sample used in the comminution test-work by our specialized partner

relationship between the uniaxial compressive strength of the nodules and their size distribution (Dreiseitl 2017; Van Wijk and Hoog 2020). Due to a lack of references to use as a point of comparison, the Low Energy Impact index and the Rod Mill Work index will not be discussed further in the present paper.

Figure 8.2 proposes a comparison between the Bond Ball Mill Work Index BWi average of polymetallic nodules, and copper, manganese, and nickel land-based ores. The graph shows the range of the historical values from Brooke and Prosser (1969) from Table 8.3, and the GSR, Deep Green, and land-based ores BWi values from Table 8.4. The differences between the average BWi of the polymetallic nodules on one hand, and between the polymetallic nodules and the copper ores on the other, do not seem statistically significant. However, on average manganese ore and nickel ore require, respectively, 27% and 33% more energy to grind the ore to P_{80} minus #100. The results should be considered with a critical perspective as the GSR value is a BWi point value, the historical range is constituted of 3 values, and the values for copper, manganese, and nickel are the averages of a large sample of ores. The Deep Green value is probably also a point value.

Nevertheless, if the trend would be confirmed for the BWi of the CCFZ nodules, and considering the absence of a requirement of primary or secondary crushing, this result is indicative of substantial energy savings for the mineral processing of CCFZ polymetallic nodules in comparison with terrestrial ores. The envisioned power density of the SAG mill (the ratio of the power of the mill to its diameter, in MW/ft) to be used for the comminution of nodules in the SAB flow sheet is far below the

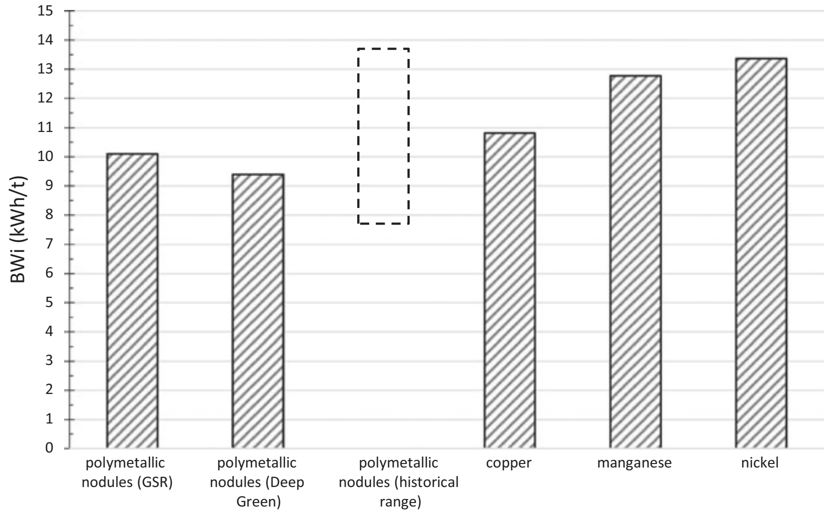

Fig. 8.2 Bond ball mill work index comparison of different ores: polymetallic nodules (GSR), polymetallic nodules from Deep Green (DeWolfe and Ling 2018)) and copper, manganese, and nickel ores

Table 8.4 Synthesis of the BWi found in literature for CCFZ polymetallic nodules and land-based ores

Dataset	BWi (kWh/t)	Source
GSR polymetallic nodules	10.1	Study by our specialized partner
Deep green polymetallic nodules	9.4	DeWolfe and Ling (2018)
Land-based manganese ore	12.8	C.f supplementary information
Land-based nickel ore	13.4	C.f supplementary information
Land-based copper ore	10.8	C.f supplementary information

power density range of 0.35–0.80 MW/ft. of the SAG mills installed by ABB in the 1995–2010 period (van de Vijfeijken 2010).

3.3 Comminution Equipment Wear Rates

Bond's abrasion test method is generally accepted as the basis for an evaluation of the attrition of metals by minerals in crushing and grinding operations (Gupta and Yan 2016). A number of correlations between the abrasion index Ai and metal wear of the liner and grinding media are used in practice. Equation (8.2) predicts the wear rate (in lb/kWh) for the balls, and Eq. (8.3) predicts the wear rate (also in lb/kWh) for the liners, both in a wet ball mill operation (Bond 1963):

$$R_{\text{balls}}\left[\frac{\text{lb}}{\text{kWh}}\right]=0.35\times\left(A_i-0.015\right)^{0.33} \tag{8.2}$$

$$R_{\text{liners}}\left[\frac{\text{lb}}{\text{kWh}}\right]=0.026\times\left(A_i-0.015\right)^{0.30} \tag{8.3}$$

The result of the test for the nodule sample abrasion index Ai is 0.001 g, which is of the same order of magnitude as the 0.0047 g value reported by Deep Green (DeWolfe and Ling 2018). This value is in the lower range of what is considered nonabrasive (Dunne et al. 2019). This characteristic is desirable to ensure the extended life of the mill linings and attrition media, and decrease the operating costs of the comminution operation (Fuerstenau and Han 2003). The nodule Ai values are so low that crusher and mill wear rates cannot be predicted with the usual empirical formulas presented in Eqs. (8.2) and (8.3).

Figure 8.3 proposes a comparison of the abrasion index value of the GSR CCFZ polymetallic nodules with typical values for nickel, copper, and manganese ores (Bond 1961a, b; Gupta and Yan 2016).

The terrestrial ore Abrasion Index values all fall under the moderately abrasive category, while the nickel ores are in the lower range of this category, and the copper and manganese ores are in the upper range (Dunne et al. 2019). The polymetallic nodules value is one to two orders of magnitude smaller than terrestrial ores, this fact being confirmed by the position of the nodules' value in the third percentile of the abrasion index database from our specialized partner. Due to their mathematical form, Eqs. (8.2 and 8.3) do not allow to predict the ball and liner wear rates for the CCFZ polymetallic nodules, but it is reasonable to assume that their wear rates would be well below 0.07 lb/kWh (for the balls) and 0.006 lb/kWh (for the liners). These are the values predicted for the nickel terrestrial ores, which are the lowest of

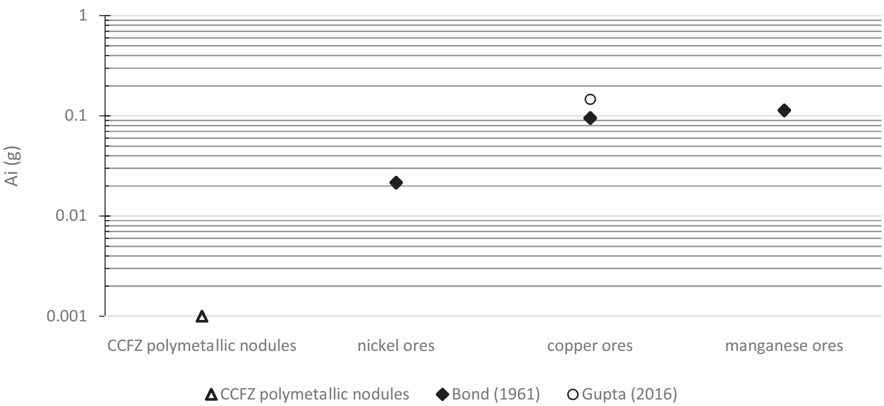

Fig. 8.3 Abrasion index comparison of polymetallic nodules and copper, nickel and manganese ores

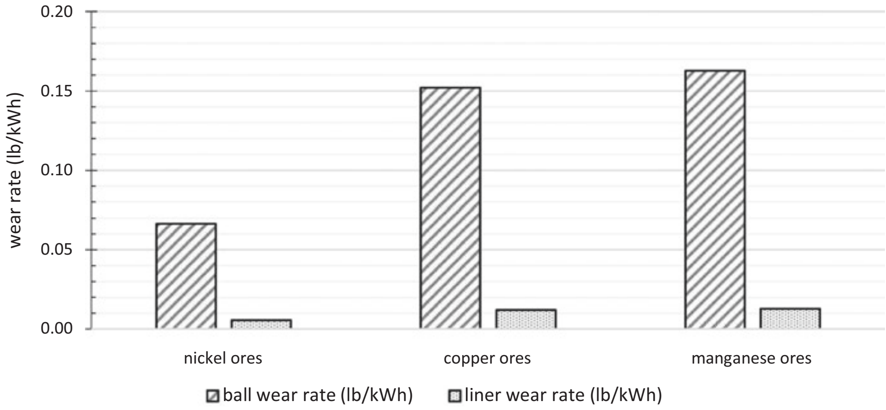

Fig. 8.4 Predicted ball wear rates for nickel, copper, and manganese ores

the set. Figure 8.4 shows the ball and liners wear rates (in lb/kWh) predicted by using the Bond abrasion index for the terrestrial ores.

This observation has important consequences: the equipment wear rates impact not only the costs due to the replacement of grinding media and worn equipment parts and the loss of production due to maintenance downtime, but also impact the pollution and contamination on the processing site, and finally, the energy that was spent for the production of the wear parts (Fuerstenau 1981). The reduced wear rate observed in the case of nodules thus considerately benefits the comminution operation.

3.4 *Metal-Specific Energy*

Comminution was already identified as a major energy consumer 40 years ago: it consumed 1% to 4% of all electrical power generated in the world (Fuerstenau 1981). Depending on the considered methodology and system boundaries, comminution represents 25% to 50% of the mine-site energy consumption (Napier-Munn 2013; Ballantyne and Powell 2014), and it is well known that comminution has a very low efficiency (3–5%) (Napier-Munn 2013). On the other hand, the energy requirement for comminution and the particle size reduction follows a Bond-like relationship depicted by Eq. (8.4).

$$W = 10\,W_{\mathrm{I}}\left(\frac{1}{\sqrt{P_{80}}} - \frac{1}{\sqrt{F_{80}}}\right) \tag{8.4}$$

where W is the comminution energy requirement (in KWh/t), W_I is the Bond work index (in KWh/t), and F_{80} and P_{80} are the 80% passing sizes of the feed and product (Bond 1961a, b).

In practical terms, this relationship means that the energy requirement will increase in a hyperbolic way with the size reduction, as one of the trends in the mining industry is to fine-grind to reach smaller liberation sizes (De Bakker 2014). Another well-known trend is the ore grade decrease (Mudd 2010; Northey et al. 2018; Rötzer and Schmidt 2020). The combination of these two trends has the potential to increase the energy requirements for comminution in a tremendous way (Napier-Munn 2013). The Bond Work Indices report the energy requirements in kWh/t, which does not incorporate the influence of the grade. Another way to report this energy requirement as a metal-specific energy per ton of final product (MSE, in kWh/ton metal) is driven by ore competence, fineness of grind, comminution efficiency, the grade of the deposit, and the separation recovery (Ballantyne and Powell 2014). This presents a totally different picture of the comminution energy requirement in the sense that the energy requirement for low-grade ores has a higher impact than for high-grade ores, a trend that will be exacerbated by the polymetallic character of the ore. In order to show that trend, we used the BWi values reported in Table 8.4 and calculated the MSE according to Eq. (8.5).

$$\mathrm{MSE}_{\mathrm{metal}}\left(\frac{\mathrm{kWh}}{\mathrm{ton\ metal}}\right) = BW_i\left(\frac{\mathrm{kWh}}{\mathrm{ton\ ore}}\right) \times \frac{\mathrm{metal\ allocation\ factor}\,(\%)}{\mathrm{grade}\,(\%\mathrm{wt.})} \tag{8.5}$$

The grade (% wt.) parameter allows to convert the value expressed per ton of ore to one expressed per ton of considered metal. The metal allocation factor allows to take into account the polymetallic character of the ore. In the case of a polymetallic ore, this metal allocation factor should represent the weight allocated to the particular metal in the basket of products, with the condition that the sum of the individual contributions of the metals would be equal to 100%. In the case of a monometallic ore, the allocation factor equals 100%. In the present paper, we used a mass allocation factor, but the method could be used with economic allocation to show a better representation of the metal-specific energy in relation to the value of the ores or metals.

In our case, we considered nickel, copper, and manganese for a comparison of the polymetallic nodules against monometallic ores, and deliberately excluded cobalt from the comparison as it is almost never a primary product (Anonymous 2019). This opens the question of the final purpose of the comparison, as individual ores could be compared using this framework, or a higher-level comparison involving a global allocation factor for nickel, copper, and cobalt as a by-product of the associated minerals could be considered as well.

For the sake of the demonstration, we used grade values reported in the literature for nickel, copper, and manganese, and the actual grades of GSR polymetallic nodules. We also used a mass allocation for the polymetallic nodules as a simple approach, however the choice of an economic allocation would not invalidate the conclusions of this discussion. Table 8.5 shows the data and the assumptions used

Table 8.5 Data and assumptions used to calculate the MSE of the polymetallic nodules and monometallic ores. A mass allocation factor of 10.9% has been considered for the cobalt in the polymetallic nodules, but the MSE_{cobalt} has not been calculated as it has been excluded from the comparison

Ore	Metal	Grade (% wt.)	Mass allocation factor (%)	BWi (kWh/ton ore)	MSE (kWh/ton metal)
Polymetallic nodules	Ni	1.3%	28.6%	10.1	221
	Cu	1.1%	10.9%	10.1	98
	Mn	27%	48.6%	10.1	18
	(Co)	(0.2%)	(10.9%)	10.1	–
Nickel ore	Ni	0.73%	100%	13.4	1830
Copper ore	Cu	0.65%	100%	10.8	1660
Manganese ore	Mn	38.7%	100%	12.8	33

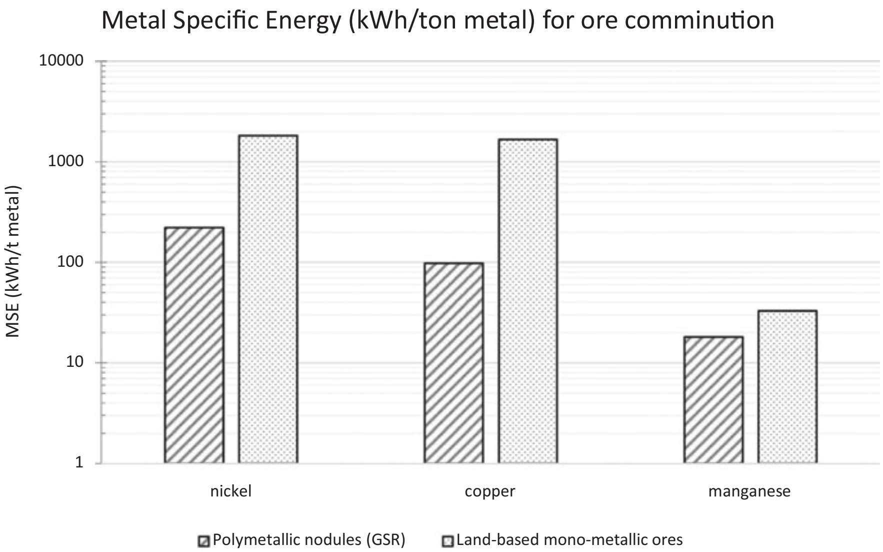

Fig. 8.5 Comparison of the nickel, copper, and manganese MSE for the polymetallic nodules and the land-based monometallic ores. Note: the vertical axis is logarithmic

for the calculations and the obtained values for the MSE of the metals associated with the considered ores.

Figure 8.5 shows the results presented in Table 8.5. It clearly shows that there is up to one order of magnitude gain that can be observed when comparing the MSE of the metals for the polymetallic nodules to the monometallic ores, whereas the BWi values in Fig. 8.2 showed a gain of 27–33% at best. This observation results from the relatively high grades and polymetallic character of the nodules, both factors that magnify the advantage of a lower BWi for the nodules in comparison with terrestrial ores.

4 Conclusion

In this chapter, a brief discussion of the relevant characteristics of deep-sea polymetallic nodules characteristics is provided, followed by a review and discussion of the manganese ore beneficiation processes and their restricted application to polymetallic nodules. It has been shown that the beneficiation of deep-sea polymetallic nodules is challenging but not impossible. There is evidence that reduction roasting preceding a separation process such as flotation or magnetic separation could be implemented in the future, most probably for three-metal business scenarios. Despite the identified limitations, there is an advantage in studying the size classification (with hydrocyclones) or gravity separation (with spiral concentrators) for polymetallic nodules in a four-metal business scenario, as the processing option can benefit from desliming and feed upgrade for the hydrometallurgical operations.

In terms of comminution of polymetallic nodules, a brief literature review is provided, putting into perspective the data obtained in a study of grindability of polymetallic nodules. The comminution study results clearly show that Bond Ball Mill Work Index and Abrasion Index values are lower than the terrestrial equivalent ores for the metals of interest. The advantage is twofold. First, the energy intensity of comminution is lower for polymetallic nodules, which leads to differences of one order of magnitude in favor of polymetallic nodules when showing the results of a comparison of metal-specific energy, a metrics that takes the grade and the polymetallic character of an ore into account. Second, values determined for the abrasion index are one to two orders of magnitude in favor of polymetallic nodules, which leads to assuming that the wear rates of the industrial comminution equipment used for nodules would be well below the values predicted for terrestrial ores.

To summarize, these results suggest there is an undisputable environmental advantage associated with the comminution of polymetallic nodules as compared to conventional (monometallic) land-based ores, due to their higher grade, polymetallic character, and comminution behavior.

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