Influence of hematite particle morphology on friable itabirite concentration in Humphreys spiral concentrator

Influência da morfologia da hematita presente em itabirito friável na concentração por espiral concentradora Humphreys

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ABSTRACT
The depletion of hematitic mineral deposits and the growing content of itabirites in the iron ores mined in the Quadrilátero Ferrífero - Brazil calls for further studies in an effort to adjust the actual technologies, due to the different behaviors of the different mineral species present in the new ore. Currently, little is known about the fundamentals of particle separation in Humphreys spiral, as far as the different particles morphologies. Therefore, the performance of a spiral concentrator was evaluated by a sequence of friable itabirite tests at an industrial scale. The smallest iron content and smaller metallurgical recovery attained in the tests owe to a small particle size in sample (33.67% < 106 µm and $d_{80} \approx 675$ µm) and a greater content of tabular hematite. The sample showing the worst metallurgical recovery results (46.20%) and iron content (62.39%) also presented the highest percentage of tabular hematite (68.69%). The samples with a greater amount of martite produced sinter feed with the highest metallurgical recovery (65.65%). It is believed that there was a predominant effect of the hematite morphology on other parameters such as density. Thus, a careful characterization step and the adoption of blending procedures concerning iron content and morphology simultaneously can be positive for the process.

Keywords: friable itabirite; Humphreys spiral concentrator; mineral morphology; metallurgical recovery.

RESUMO
O esgotamento dos depósitos minerais hematíticos e o aumento da proporção de itabiritos nos minérios de ferro extraídos do Quadrilátero Ferrífero - Brasil exigem mais estudos no esforço de adequar às tecnologias atuais, devido aos diferentes comportamentos das diferentes espécies minerais presentes no novo minério. Atualmente, pouco se sabe sobre os fundamentos da separação de partículas na espiral de Humphreys, no que diz respeito às diferentes morfologias das partículas. Portanto, o desempenho de um concentrador espiral foi avaliado por uma sequência de testes de itabirito friável em escala industrial. O menor teor de ferro e menor recuperação metalúrgica obtida nos testes devem-se ao pequeno tamanho de partícula na amostra (33,67% <106 µm e $d_{80} \approx 675$ µm) e maior conteúdo de hematita tabular. A amostra que apresentou os piores resultados de recuperação metalúrgica (46,20%) e teor de ferro (62,39%) também apresentou o maior percentual de hematita tabular (68,69%). As amostras com maior quantidade de martita produziram sínter feed com maior recuperação metalúrgica (65,65%). Acredita-se que houve um efeito predominante da morfologia da hematita sobre outros parâmetros como densidade. Assim, uma etapa de caracterização cuidadosa e a adoção de procedimentos de mistura quanto ao teor de ferro e morfologia simultaneamente podem ser positivas para o processo.

Palavras-chave: itabirito friável; espiral concentradora Humphreys; morfologia mineral; recuperação metalúrgica.

1 INTRODUCTION

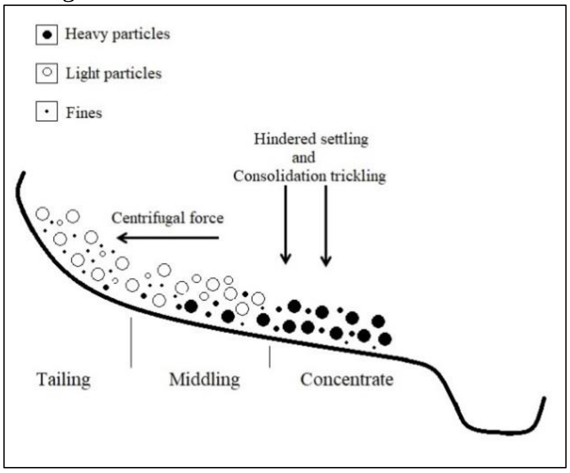
The depletion of hematitic mineral deposits and the growing content of itabirites mined in the *Quadrilátero Ferrífero* - Brazil have encouraged the development of process that enable the use of technologies dedicated to the concentration of finer granulometric fractions and wide mineralogy presented. This fact renders the importance of developing more efficient process routes that allow the maximization of the recovery rates and reduction of the tailings volume produced uppermost. Nascimento *et al.*, 2020 exposed the importance of studying options such as dry ore processing as a way to reduce the use of dams and the high consumption of water. On the one hand, dry processing can cause inefficiencies in mineral processing, and, therefore, improving the efficiency of technologies that are in use may be a better choice.

A specific mine in the *Quadrilátero Ferrífero* (Brazil) produces sinter feed from friable itabirites, amongst other products. As the friable itabirite can present high iron content in the finer fractions, typically in the granulometry less than 100 µm, the use of the spiral concentrator may be inefficient. The presence of the aforementioned lithological types in the ore expected to feed the beneficiation plant in the coming years will increase, therefore, it will be necessary to operationalize the fine sinter feed concentration plant, that employing spiral concentrators today.

Amongst all technologies applying gravity concentration, Humphreys spiral concentrator (devised in 1941 by Ira Boyd Humphreys) (Sampaio and Tavares, 2005) is to be highlighted. The spiral concentrator shape involves a semi-circular layout around a vertical axis (Sivamohan and Forssberg, 1985) and can process different types of ores, particularly those presenting coarse particle sizes, intended for the production of specific commodities, including sinter feed (Valadão *et al.*, 2007). When the pulp (solids percentage between 15 and 45% and particles sizes from 75 to 3000 µm) is fed into a spiral concentrator, the flow goes spirally downwards promoting stratification of the particles, given the combined effects of the centrifugal force, differential settling, and interstitial trickling on the particle bed (Figure 1).

Different morphologies attributed to grains of hematite already were identified, i.e., granular hematite, tabular hematite, martitic hematite, polycrystalline hematite, hematite-goethite aggregates, and goethite. The granular hematite is observed as grains with irregular surfaces, the tabular hematite consists of grains with plain to concave surfaces, and the martitic hematite grains show triangular sections derived from the topotactic transformation of magnetite to hematite. The high porosity of the martitic hematite grains is another evidence of the magnetite transformation to hematite (Barbosa and Lagoeiro, 2009; Barbosa *et al.*, 2011).

Figure 1- Illustration of particle bed stratification in a Humphreys spiral concentrator. The concentration in the spiral concentrator occurs through operational adjustments that affect the hindered settling, consolidation trickling, and centrifugal force action.



Source: authors

The Humphreys spiral concentrators have low efficiency in cases of fine particle concentrations, particularly when sizes are smaller than 75 µm, however, the influence of particle morphology is not thoroughly addressed. Spottiswood and Atasoy (1995), pointed out although particle separation is a widespread gravitational technology, little is known about the influence of different morphologies (i.e., for the same mineral species) associated with different particle sizes. In this context, the objective of the current work is to evaluate the effects of different particle sizes and associate the morphology of the hematite in a friable itabirite used in the production of fine sinter feed.

2 METHODS

2.1 ORE PREPARATION

Five samples of friable itabirite from a specific mine in the *Quadrilátero Ferrífero* (Brazil) were used in the concentration tests, coined sample 01 (SM-01), sample 02 (SM-02), sample 03 (SM-03), sample 04 (SM-04), and sample 05 (SM-05). The samples were collected by the geology team, which respected the sampling procedures of the company. Six tons of ore were sampled at five defined sites in the mine.

Each sample (approximately 1.2 tons) was prepared initially by sieving (sieve with a 1000 µm aperture), and the particles retained were stored. The undersize product (< 1000 µm) was deslimed in a spiral classifier and was used as the feed of the concentration tests. Desliming was performed as a means of eliminating the negative effect of the slime-coating caused by the slime particles (<< 38 µm). Sieving and desliming allowed the adjustment of the particle sizes to ranges between 150 and 1000 µm.

2.2. SAMPLE CHARACTERIZATION STEP

Granulometric analyses were made by using Tyler® series of sieves to determine the size distribution of the five samples prepared.

The mineralogical study of each sample (-1000 +150 µm), as well as the liberation ratios were carried out by optical microscopy by employing a Leica DM 2500P® Microscope, through a coupled image capture system and Zeiss Stemi DV4 series stereomicroscope. However, the liberation indexes were estimated by using the polished sections made with the aliquots retained in each cited sieves.

The chemical analyses were performed by x-ray fluorescence in order to characterize the samples and product composition, regarding the iron and silica contents.

The results, representing average values from the analysis in more than one step, showed a standard deviation (2σ) < 5%.

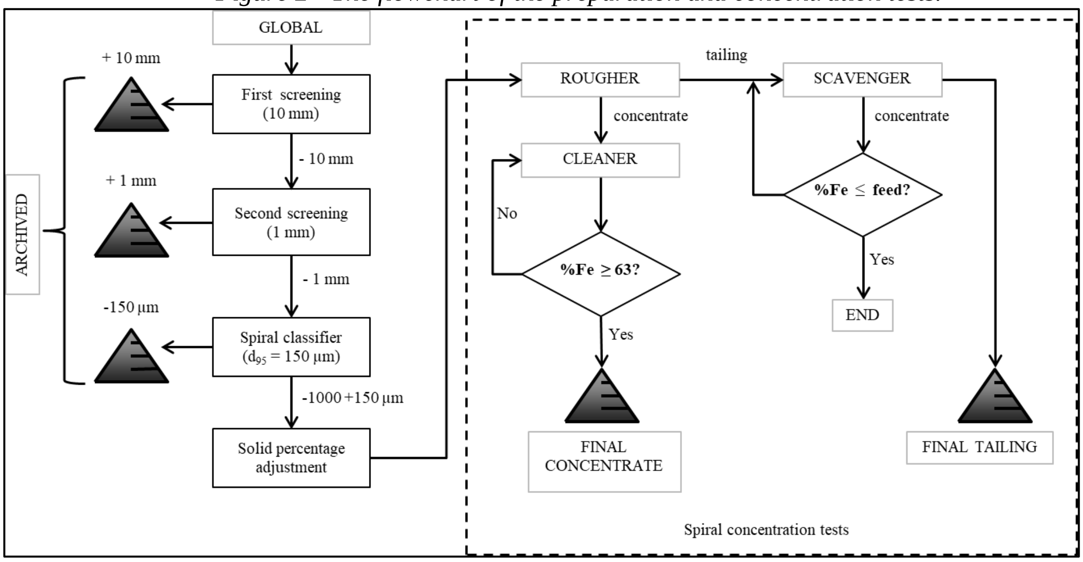
2.3. ADJUSTMENT OF THE SPIRAL CONCENTRATOR AND CONCENTRATION TESTS

A system consisting of a loop containing a centrifugal pump coupled to a feed box was used in the tests, the equipment was connected to the spiral feed distributor (rate of 1t/h). Thus, it was possible to adjust the operating conditions (solids percentage and feed rate) for a pulp flow as constant as possible, in order to achieve effective concentration tests.

Water was added to the sample to produce a pulp having a 35% of solids (w/w). The spiral concentrator (HG-10, Mineral Technologies®, industrial-scale with 5 turns) was fed at the rate of 4.5 m^3/h. The system was operated in a closed circuit with the flows of concentrate and tailings returning to the loop feed box until the circuit reached stabilization and the experimental conditions for each ore type were equal.

Figure 2 shows a flowchart of the preparation and concentration tests conducted through rougher, cleaning (final concentrate), and scavenger (final tailing) stages.

Figure 2 - The flowchart of the preparation and concentration tests.



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After the flow was stabilized, samples of the tailings and concentrate were collected in appropriate containers, previously identified. Aliquots were sampled for physical and chemical characterization. The aforementioned parameters (feed rate and solids percentage) were maintained in the cleaner and scavenger stages during the concentration process. The main parameter used in the assessment of the performance of the process was the iron content in the concentrate, which should be equal or greater than 63%.

Considering the rougher, cleaning, and scavenger stages, the experiment comprised a total of 15 runs in an industrial spiral concentrator and processed 6 tons of ore. The Bilco® mass balance software was used for all calculations, such as metallurgical recoveries.

3 RESULTS AND DISCUSSION

3.1. CHARACTERIZATION STEP

Table 1 shows the different particle morphology, as identified by mineralogical studies. It was observed that the hematite (the predominant iron oxide) presented various morphologies, representative of the itabiritic. Amongst all the types of hematite presented, the tabular type was predominant in sample SM-01, martitic hematite in appeared in SM-04, and lobular type in SM-05. Regarding samples SM-02 and SM-03, both had an equal proportion of tabular hematite and martitic hematite, whereas quartz was the main gangue mineral.

Table 1 - Morphological types observed on the samples prepared (-1000 +150 µm).

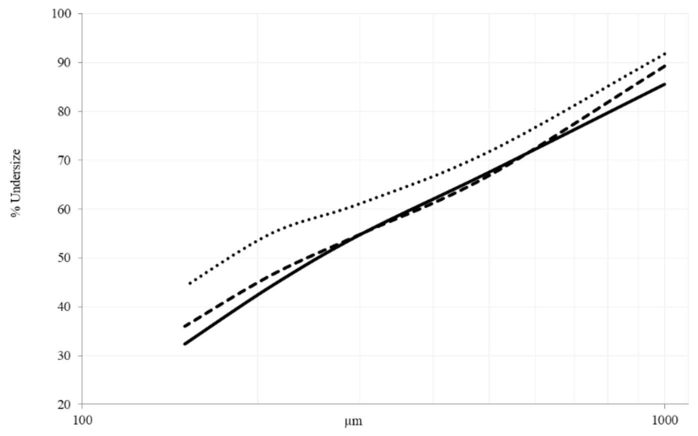
Sample	Tabular Hematite	Granular Hematite	Martitic Hematite	Lobular Hematite	Magnetite	Goethite	Quartz	Others
SM-01	**68.69**	0.76	0.66	0.00	0.69	5.29	21.28	2.63
SM-02	**28.11**	0.17	**37.92**	5.87	1.37	6.96	18.28	1.32
SM-03	**32.57**	0.31	**37.16**	0.75	1.08	12.02	10.98	4.15
SM-04	3.24	0.01	**65.77**	2.32	4.65	11.87	12.28	1.01
SM-05	2.43	14.12	1.30	**60.74**	2.29	1.61	17.38	0.12

Source: authors

Regarding the mineral liberation study, it was found that the samples showed a liberation index greater than 70% (for iron oxide minerals). This liberation index can be satisfactorily accepted since intense grinding aiming the higher indexes can generate many fines (d << 106 µm) and compromise the gravitational concentration processes, because the existence of particles smaller than 106 µm can cause a sharp decline in the dense product recovery rates. Furthermore, according to Holtham (1992), this decline can be attributed to the action of Bagnold's forces in the viscous medium.

Figures 3 and 4 show the results of granulometric and chemical analyses of five samples (-1000 +150 µm) that constituted the feed of tests. The iron and silica contents were enhanced due to the important role they play in the evaluation of the concentration process. The d_{80} was used as a comparison parameter for size particles analyses. The sample SM-01 showed the finest size, with a d_{80} of approximately 675 µm, the lowest iron content (51.80%), and the highest silica content (24.20%). On the other hand, the sample SM-04 showed the greatest iron content before concentration (61.30%).

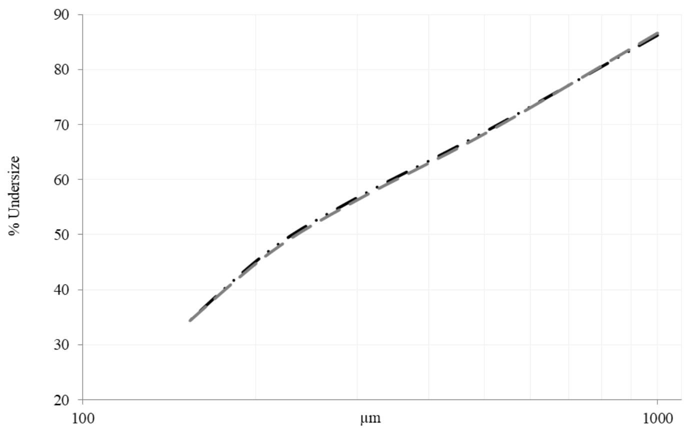
Figure 3 - Granulometric and chemical analysis of samples 01, 02, and 03. [Standard deviation (2σ) < 5%].



	d_{80} (µm)	COMPOSITION	
		%Fe	%SiO_2
SM-01	≈ 675	51.80	24.20
SM-02	≈ 750	55.40	18.00
SM-03	≈ 825	56.50	14.70

Source: authors

Figure 4 - Granulometric and chemical analysis of samples 04, and 05. [Standard deviation (2σ) < 5%].



	d_{80} (µm)	COMPOSITION	
		%Fe	$\%SiO_2$
SM-04	≈ 775	61.30	10.50
SM-05	≈ 775	56.40	17.80

Source: authors

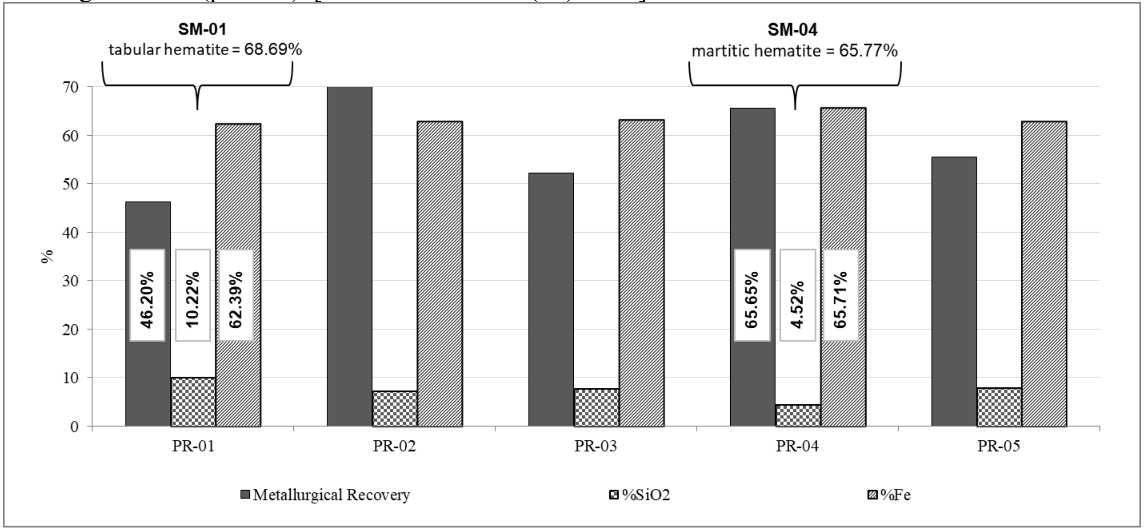
3.2. CONCENTRATION TESTS RESULTS

3.2.1 Effect of morphology

By using the Bilco® mass balance software, the data of contents (iron and silica) and granulometry were established and the concentration test results were obtained for each friable itabirite - middling was not observed in this study.

The granulometric distribution of the samples and the morphology of the iron oxide particles, mainly the presence of tabular hematite, exerted a decisive influence on the performance of the spiral concentrator. These findings justify the iron content data and the metal recovery obtained in the concentration tests (Figure 5) conducted with the sample SM-01 (now product 01, PR-01), which was characterized by the lowest iron content, the highest amount of tabular hematite and the highest proportion of the smaller particles (33.67% < 106 µm and $d_{80} \approx 675$ µm, Figure 3). On the other hand, the product PR-04, from the sample SM-04, was the one that showed the best results in a joint analysis of recoveries and content. The SM-04 sample presented the highest percentage of martitic hematite (65.77%).

Figure 5 - Metallurgical recovery and contents of iron; silica for each product. Note: SM (sample) was exchanged for PR (product). [Standard deviation (2σ) < 5%].



Source: authors

Arroyo (2014) states that hematites developed in regions of metasomatic contact are commonly tabular, they generally occur in the lamellar form. The lamellar form allows the dragging of the tabular particles to the tailings by the water flow. Tabular particles, however dense, are susceptible to the dragging forces exerted by the fluid, and they are likely to be dragged to the periphery of the spiral, as occurs to the light particles.

Barbosa (2009), using a microscope of polarized reflected light, found that the tabular hematite crystals were surrounded by thin layers of quartz and iron hydroxide, which can interfere in the concentration process, resulting in the dilution of the concentrate. Furthermore, the association of quartz and iron hydroxide, more prominent on tabular hematite, can cause a reduction in density, therefore contributing to losses to tailings during concentration. Despite being heavier than gangue minerals, tabular hematite fine particles can behave similarly to light particles, justifying this loss.

The few data about the densities of the different hematite morphologies (tabular hematite = 5.14 g/cm^3; martite = 5.06 g/cm^3 (Graça *et al.*, 2016)) point to a small variation in this parameter, thus suggesting in this specific case, that the gravity concentration is dependent more with the shape of the particles than the others parameters.

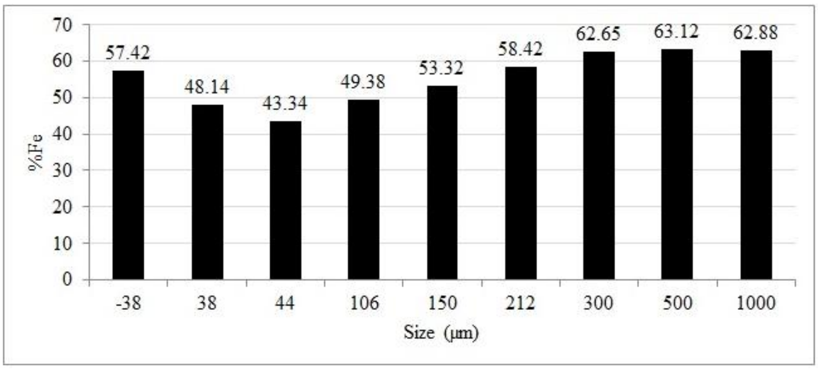
3.2.2 Effects of fines

The objective at this point was to implement the discussion in a synergistic way, regarding the effects of the predominant size and morphology of the hematites in the concentration process.

In regard to the mass recovery from the final concentrate in the five tests, conducted with the spiral concentrator, it should be noted that a concentrate having a particle size smaller than 106 µm suffered a sharp fall in the mass recovery rate (from 56.41% to 21.25%), which confirmed the negative effect of the particles rated as fine. Several authors highlight the difficulties in concentration ore fines, as cited by Subrahmanyam and Forssberg, 1990 and emphasized in research by Nogueira *et al.*, 2020. Also, the fine particles (especially those smaller than 106 µm, which amounts to 50% of the metallic content of the feeding samples) (Figure 6), were dragged to the tailings by the water action.

Deng (2015) noted that dense particles smaller than 106 µm are very likely to be rejected during the concentration process, however, they are of interest. Deng also associates the possible effects that the so-called secondary flow, known as the “river bend effect” (Holland-Batt, 1992b) with losses. The secondary flow consists of an outward flow in the top layers of a pulp and an inward flow in the bottom fluid layer close to the trough surface.

Figure 6 - Average contents of iron in the function of the average particle size. [Standard deviation (2σ) < 5%].



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According to Holtham (1992), the concentration of fine particles in the dense region can be attributed to the effects of Bagnold’s forces, whose action in the viscous field causes the elevation of these particles, by keeping them suspended in the upper layers of the fluid preventing them from permeating the internal secondary flow, i.e., the dense product region. It is important to note that low recovery rates observed in finer particles occurred despite the fact that the average iron content was above 40% (as showed in Figure 6). Moreover, this phenomenon contributed decisively to the low mass and metallurgical recovery rates, whose averages assigned 43.74% and 49.11%, respectively.

4 CONCLUSION

The sample showing the worst metallurgical recovery results (46.20%) and iron content (62.39%) also presented the highest percentage of tabular hematite (68.69% w/w). On the other hand, the processing of samples with a greater amount of martite produced sinter feed with the highest metallurgical recovery (65.65%). It is believed that there was a strong contribution of the hematite morphology on other parameters, such as density. Tabular hematite can be associated with considerable amounts of quartz and goethite, which have smaller densities, thus reducing the effect of the sedimentation and consolidation of the particles. This phenomenon can be intensified by reducing the size of the particles.

Tabular particles, considered dense when compared to those with an isometric shape, are susceptible to the drag forces exerted by the fluid, being more easily dragged to the periphery of the spiral, behaving in a similar way to the light particles. Thus, a careful characterization step and the adoption of blending procedures concerning iron content and morphology simultaneously can be positive for the process.

The low recovery rate of finer particles can be appointed as being one of the possible causes of the reduced mass and metallurgical recovery values observed in the tests, whose averages were 43.74% and 49.11%, respectively.

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