# DEINKING SELECTIVITY (Z-FACTOR): A NEW PARAMETER TO EVALUATE THE PERFORMANCE OF FLOTATION DEINKING PROCESS

**J.Y. Zhu,* F. Tan, and K. L. Scallon**

USDA Forest Service
Forest Products Laboratory
Madison, Wisconsin 53726–2398, USA

**Y. Zhao and Y. Deng**

School of Chemical and Biomolecular Engineering
Georgia Institute of Technology
Atlanta, Georgia, USA

## ABSTRACT

Reducing fiber loss is also important to conserve resources and reduce the cost of secondary fibers. This study proposes a deinking selectivity concept that considers both ink removal and fiber yield in determining the performance of deinking operations. The defined deinking selectivity, or Z-factor, is expressed by the ratio of ink removal expressed by the International Standards Organization (ISO) brightness gain or the reduction in relative effective residual ink concentration (ERIC) and the relative fiber rejection loss. Pilot-scale flotation deinking experiments showed that Z-factor weighted brightness gain and ERIC reduction are good indicators of deinking process efficiency. The Z-factors are good indicators of the efficiency of a deinking stage or process. A simple criterion developed using the stage Z-factor was applied to a mill operation to determine the stage economics.

## INTRODUCTION

Flotation deinking has been adopted as a standard practice for removing ink from wastepaper in paper recycling operations. Ink is removed when the ink-attached bubble froth floats to the top of a flotation cell and is rejected. An increase in froth rejection rate results in an increase in ink removal. Unfortunately, the bubble froth rejection process also rejects fibers, primarily as a result of the entrainment of fiber into the bubble network [1–5]. Furthermore. fiber rejection loss is increased with an increase in froth rejection [3]. It is apparent that increased ink removal and fiber yield are two contradictory requirements in flotation.

Because the primary concerns in most paper recycling mill operations are machine or process runnability and meeting the ink removal specifications of customers without additional processing (e.g., bleaching), most studies on flotation deinking have primarily focused on removal of contaminants. These studies include understanding pulping chemistry and process [6–10] on ink separation from the fibers, removal of wax or stickies through flotation [11,12]. and flotation chemistry to improve ink removal [13–19]. Typical gains of paper brightness around 10% ISO standard [20] through flotation are common in laboratory or mill operations. Little attention has been paid to the improvement of fiber yield in flotation. After studying the fiber entrapment mechanism of fiber loss in flotation deinking [5, 21], water spray was used to reduce the fiber trapped in the froth and thereby increase yield in a laboratory study [21]. A frothing agent spray concept was proposed to obtain separate control of froth stability to increase fiber yield and optimize ink removal in deinking of toner printed papers in laboratory [4]. This concept was later successfully demonstrated using a mixture of old newsprint (ONP) and old magazine (OMG) furnish in a pilot-scale flotation cell [22]. Typical yield losses in recycling mill operations are about 10% to 25%. Because fiber loss is mainly caused by the same process for ink removal, i.e., froth rejection. it is logical to take an integrated approach to evaluate flotation deinking performance. That is, the flotation process has to be optimized in terms of both high ink removal rate and fiber yield. The objective of our study was to define a deinking selectivity concept that takes into consideration both ink removal and fiber loss process for balanced evaluation of industrial deinking processes.

## DEFINITIONS

The ratio of deinking brightness gain and percentage of relative fiber loss was used to describe flotation deinking selectivity in our previous study [22]. It was found that the defined selectivity was effective in differentiating the overall performance of several flotation experiments under various conditions, which led to the definition of selectivity in general terms in this study.

### Instantaneous Deinking Selectivity

Instantaneous deinking selectivity, $Z(t)$, is defined as

$$Z(t) = \frac{dG}{dFrj} \quad (1)$$

where G is the relative percentage of change of any ink removal parameter, e.g.., ISO brightness gain (GB), relative effective residual ink concentration (ERIC) reduction (RE) etc., and *Frj* is the percentage of fiber rejection loss. Therefore, instantaneous brightness and ERIC selectivity are defined as

$$Z_B(t) = \frac{dGB}{dFrj} \quad (2a) \qquad Z_E(t) = \frac{dRE}{dFrj} \quad (2b)$$

### Time-Averaged Period or Stage Selectivity (or Z-Factor)

In practice, time-averaged deinking selectivities over a short period, e $t_i$, are often used:

$$Z(\Delta t_i) = \frac{\Delta G_i}{\Delta Frj_i} \quad (3)$$

$$Z_B(\Delta t_i) = \frac{\Delta GB_i}{\Delta Frj_i} \quad (4a) \qquad Z_E(\Delta t_i) = \frac{\Delta RE_i}{\Delta Frj_i} \quad (4b)$$

The importance of time-averaged period deinking selectivities is their application in various flotation stages in mill operations. When the relative changes of ink removal parameters, i.e., brightness gain or ERIC reduction, and relative fiber loss are evaluated for an individual flotation stage (with typical residence time of 1 to 2 min), the calculated time-averaged period selectivities are the selectivities of the individual stage. For this reason, the time-averaged period selectivities can be called stage deinking selectivities. or simply stage Z-factors.

### Accumulative Selectivity (Process Selectivity or Z-Factor)

Accumulative deinking selectivity or Z-factor is used to evaluate the overall performance of the deinking process. It is the extension of time-averaged selectivity from a short period to the whole process.

$$Z(T) = \frac{\sum_i \Delta G_i}{\sum_i \Delta Frj_i} = \frac{G(T)}{Frj(T)} \quad (5)$$

$$Z_B(T) = \frac{\sum_i \Delta GB_i}{\sum_i \Delta Frj_i} = \frac{GB(T)}{Frj(T)} \quad (6a) \qquad Z_E(T) = \frac{\sum_i \Delta RE_i}{\sum_i \Delta Frj_i} = \frac{RE(T)}{Frj(T)} \quad (6b)$$

where *T* is pulp suspension residence time in whole flotation process of various stages.

**Selectivity or Z-Factor Weighted Brightness Gain and ERIC**

Selectivity or Z-factor does not give the absolute value in brightness gain or ERIC reduction through the process or a particular stage. It is logical to define Z-factor weighted brightness gain and ERIC (Eq. (7)) for absolute or quantitative comparison of ink removal through various processes or stages.

$$BG_{ZB} = Z_B \cdot BG \quad (7a) \qquad RE_{ZE} = Z_E \cdot RE \quad (7b)$$

where $BG_{ZB}$ and $RE_{ZE}$ are the brightness and ERIC Z-factor weighted brightness and ERIC reduction. respectively. In most flotation processes, typical brightness Z-factor is on the order of unit value. Therefore, a brightness Z-factor weighted brightness gain is on the same order of magnitude of ordinary brightness gain and has relevance to the brightness gain used in current industrial practice. While typical ERIC Z-factor is on the order of 10 units, the ERIC Z-factor weighted ERIC reduction will be only an order of magnitude greater than the ordinary ERIC reduction. It is not possible to have infinitively large Z-factors. which would distort the intended meaning of the Z-factor weighted brightness gain and ERIC reduction, because there is always a finite value of fiber loss in industrial unit operations. As will be discussed, large Z-factor values are possible as a result of the rejection of a very small amount of fibers, which only occurs during the start-up of the system. However, small stage, process, or accumulative Z-factors are possible in the later stages of a unit operation as a result of the typical kinetic behavior of ink removal and constant fiber rejection. Small Z-factors can lessen weighted brightness gain and ERIC reduction. which is the intended purpose of the two parameters defined by Eq. (7).

**Economic Significance of Deinking Selectivity or Z-Factor**

Assuming that the pulp price gain for an additional unit of ink removal (e.g., one unit of brightness gain or ERIC reduction) is $\Delta P_G$ and that the additional percentage of fiber loss to achieve the additional unit of ink removal $\Delta G$ is $\Delta Frj$ through the flotation stage or processing under evaluation, then the economic gain of unit ton pulp can be calculated as expressed by the left-hand side of inequality in Eq. (8). The economic gain has to be positive to justify the additional flotation stage or any further processing; i.e., the following expression must be held:

$$(P + \Delta P_G \cdot \Delta G) \cdot (1 - \Delta Frj/100) - P > 0 \quad (8)$$

Recalling the definition of stage Z-factor in Eq. (3). the following criterion can be obtained from Eq. (8):

$$Z > \frac{1}{\frac{\Delta P_G}{P} \times 100} + \frac{\Delta G}{100} \quad (9) \qquad Z > \frac{1}{\frac{\Delta P_G}{P} \times 100} \quad (10)$$

$\Delta G/100$ is often an higher order term and was ignored in Eq. (10). Equation (10) clearly indicates that the stage Z-factor must be greater than the inverse of the percentage of pulp sale price gain from the additional unit of ink removal to justify the additional flotation stage or process. Note that this criterion does not take into account the lost production resulting from increased residence time in the additional stage.

## EXPERIMENTAL

Experiments were conducted in the pilot plant flotation deinking facility at the USDA Forest Products Laboratory, to illustrate the practicality of the defined Z-factors and their associated deinking parameters. The facility consists of a two-stage Lamort (Kadant Lamort, France) vertical flotation cell of capacity of 2,000 L. The flotation cell has concentric inner and outer chambers, each about 1,000 L, as the two stages. All the experiments conducted were run in batch mode.

Fiber suspension feedstock was injected into the flotation cell through eight tangential jets in the inner chamber. Pressurized air was pumped by venturi devices through the jets into the inner and outer chambers of the flotation cell. The flotation air flow rate was set at 10 scfm for most experiments and 15 scfm for one experiment. After entering the bottom of the inner chamber, the fiber suspension feedstock swirled upward, carrying entrained air and ink particles. The feedstock spilled into the outer chamber. At the top of the stock interface a vacuum manifold suctioned off the top layer of foam attached with ink particles produced by air flotation. To obtain good mixing, suspension stock was drawn from the bottom of the outer chamber, then recirculated tangentially through three jets to the bottom of the outer chamber. Air was also injected through the three recirculating jets using venturi devices. The air recirculation pressure was maintained at 62 kPa in all experiments. The flotation accept stream was removed from the bottom of the outer cell. The typical distance between the suction shoe and the top suspension interface was maintained at about 2 cm in most operations.

Old newsprint (ONP) was obtained from London, England (Daily Mad. August–September 2002). Before experimentation, the newspapers were sorted to remove inserts. Old magazine papers (OMG) were obtained from Quad Graphics (Sussex, Wisconsin). The ratio of ONP and OMG in the wastepaper for pulping was 9:1. The ash content of the feedstock from the pulping of the ONP and OMG mixture was about 5.6%. Commercial deinking chemical Lionsurf 5140, Kemira Chemicals, Kennesaw, Georgia was used for all experiments. The chemical charge on oven-dry (OD) weight of paper was varied from 0.2 to 0.8, which gave a range of chemical concentration in the suspension of 13.6 to 54.4 mg/L. To obtain time-dependent data from the flotation processes, reject and accept samples were collected every 3 to 5 min. depending on the duration of the batch flotation. Feedstock samples were also collected for each experiment.

Handsheets made from wet samples were used for ERIC measurements by Technidyne Corp. (New Albany, Indiana). Five readings were made for each pad. TAPPI method T218 om–91 [20] was used to make a pad from wet samples to determine the consistency of solid and ash content in the feedstock and reject stream through combustion at 525°C and for brightness measurements (TAPPI T525 om−92[20]). A total of six readings from two pads were made.

## RESULTS AND DISCUSSION

### Accumulative (Process) Z-Factors–Effect of Chemical Charge

It is well known that increasing the deinking surfactant charge initially increases ink removal as a result of the increase in froth stability [4,5,15,16,19]. Further increasing surfactant charge in the flotation stock reduces ink removal as a result of the reduction of the hydrophobicity of ink particle surfaces caused by the adsorption of surfactant. This effect of deinking surfactant on ink removal was observed (Fig. 1). The data shown in Fig. 1 were obtained from four separate batch experiments after 15 min of flotation. The results indicate that the best ink removal in terms of brightness gain and ERIC could be obtained in a chemical charge around 0.4% (The 0.35% chemical charge caused by chemical pump malfunction was designed to repeat the 0.4% experiment.) For the two experiments conducted at chemical charges of 0.4% and 0.8% the 0.8% charge resulted in slightly more ink removal, based on the brightness and ERIC data, which does not rule out the adoption of a 0.8% chemical charge, assuming the difference in chemical cost between it and a 0.4% charge were insignificant. However, evaluation of the Z-factors. Z-factor weighted brightness gain, and ERIC led to the conclusion that the 0.4% chemical charge is optimal (Figs. 2 and 3). Both brightness and ERIC Z-factor obtained at 0.4% chemical charge were about 70% greater than values obtained at 0.8% chemical charge, as a result of the significant increase in fiber rejection loss under the 0.8% deinking chemical charge, which, in turn, was caused by the increase in froth stability and consequent entrapment of fibers [5,21]. Fiber loss linearly increased with the increase in deinking chemical charge (Fig. 4). The y-intercept at zero chemical charge can be considered as the fiber loss resulting from true flotation [5], which was only 2% for the 15-min flotation conducted. Figure 4 indicates that an appropriate frothing agent charge not only reduces chemical cost but also increases fiber yield.

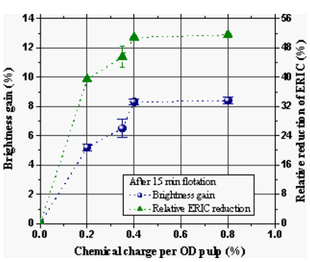


**Fig. 1 Effect of chemical charge on fiber brightness gain and ERIC reduction.**

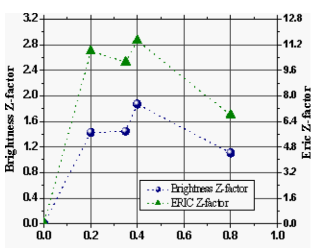


**Fig. 2 Effect of chemical charge on deinking process selectivities.**

To further investigate the performance of the two flotation processes at chemical charges of 0.4% and 0.8% we plotted time-dependent brightness gain and ERIC reduction. As shown in Fig. 5, the two processes were essentially identical if judged on the basis of ink removal. However, it becomes evident that the process using 0.4% chemical charge is preferable when the time-dependent fiber loss data are plotted as shown in Fig. 6. Fiber loss was linearly dependent on flotation time in both runs, but the slope was lower for the 0.4% charge. The negative intercepts of the linear regression results of the fiber loss data were due to the unsteadiness of the two batch processes during the start-up period. The comparison of the two processes can be easily illustrated by using the cumulative or process Z-factors. As shown in Fig. 7, both the cumulative brightness and ERIC Z-factors of the 0.4% chemical process were consistently higher than those of the 0.8% process at any given flotation time.

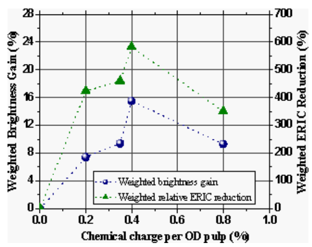


**Fig. 3 Effect of chemical charge on Z-factor weighted brightness gain and ERIC reduction**

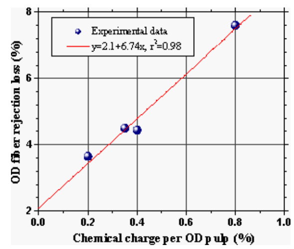


**Fig. 4 Effect of chemical charge n on fiber rejection loss.**

This discussion indicates that it is insufficient to judge deinking performance from ink removal data only. The Z-factor weighted brightness gain and relative ERIC reduction shown in Fig. 3 illustrate how these two parameters can be used to determine the overall performance of a deinking operation without losing the conventional meaning of ordinary brightness gain and ERIC reduction.

### Period Z-Factor — Effect of Flotation Residence Time

To illustrate the period Z-factor concept, the time-dependent brightness gain, ERIC, and fiber loss, collected at 5-min intervals at chemical charge 0.35% were used to calculate period Z-factors. As shown in Fig. 8, the period Z-factor follows the law of deminishing return due to the kinetic behavior of ink removal and continued near-constant rate of fiber loss. The period brightness Z-factor was about 4 in the first 5 min of flotation and decreased to about 0.2 after another 20 min of flotation, whereas the ERIC Z-factor was decreased from 56 to about 0.6 in the same period. The data clearly indicate that the last 5 min of flotation were inefficient. A pulp sale price gain of more than 5% for unit brightness gain and/or a 1.6% price gain for an ERIC reduction of 1% is required to make the last period of flotation economical.

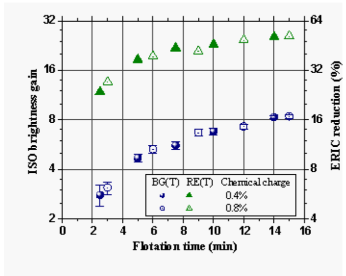


**Fig. 5 Time-dependent rightness gain and ERIC reduction under two deinking chemical charges.**

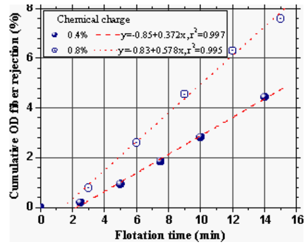


**Fig.6 Time-dependent fiber rejection loss under two deinking chemical charges.**

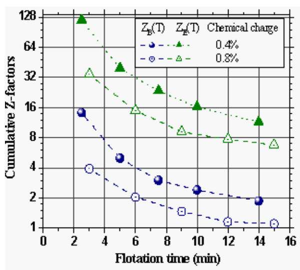


**Fig 7. Time-dependent cumulative selectivities (Z-factors) of two flotation deinking process.**

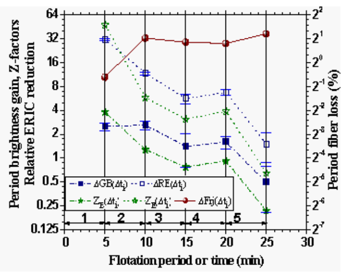


**Fig. 8 Time-dependent period brightness gain, ERIC reduction, fiber loss, and Z-factors.**

## Stage Z-Factors— Flotation Stage in Industrial Operation

We applied the stage Z-factor concept to a mill flotation deinking operation to determine the efficiency of each flotation stage at the mill. To conduct this exercise, we sampled the feed and accept stock of different stages of a production line with seven stages in series. Determination of the reject flow rate of each stage was not possible and was not attempted. Therefore, fiber loss was estimated from the consistency of the stock in each stage. The results indicate that consistency decreases linearly across the seven stages. Therefore, a constant of 1/7 of total fiber loss determined from the consistency of the feed and final accept stock was used as the fiber loss for each stage.

Handsheets were prepared from the sampled pulps to measure the brightness and ERIC of the deinked fibers. We determined the deinking selectivity or Z-factor of each stage. As listed in Table 1 both the brightness and ERIC Z-factors decreased exponentially across the seven stages as a result of exponential decay of ink removal through the stages downstream. We then calculated the required pulp price gain for economical operation of each stage according to Eq (10).

The results indicate that the last two stages are not economically justified according to this sampling exercise. The required pulp price gain per unit brightness gain was over 10%. while the pulp price gain for each percentage of ERIC reduction required for the last stage to be economical was 27%. This exercise demonstrates the practical importance of the deinking selectivities or Z-factors defined in this study.

## Z-Factor Weighted Brightness Gain and ERIC Reduction—Comparison of Flotation Processes Under Various Operation Conditions

To further illustrate how Z-factor weighted brightness gain and ERIC reduction can be used to determine deinking performance, batch flotation experiments were also conducted under various experimental conditions; i.e., various fiber rejection rates made by adjusting the distance between the suction shoe and the suspension top surface, different chemical charges, and different recirculation air flow rates.

**TABLE 1 DEINKING PERFORMANCE OF INDUSTRIAL 7-STAGE FLOTATION OPERATION**

| | Brightness | ERIC | Consistency | $Z_{Bi}$ | $Z_{Ei}$ | ΔP/P (%) per unit ISO | ΔP/P (%) per % RE |
|---|---|---|---|---|---|---|---|
| Feed | 44.17 | 1177 | 0.0087 | | | | |
| Stage 1 | 51.27 | 574.2 | | 6.179 | 44.574 | 0.16 | 0.02 |
| Stage 2 | 53.32 | 428.6 | | 1.784 | 10.766 | 0.56 | 0.09 |
| Stage 3 | 54.68 | 363.1 | | 1.184 | 4.843 | 0.84 | 0.21 |
| Stage 4 | 55.51 | 303.4 | | 0.722 | 4.414 | 1.39 | 0.23 |
| Stage 5 | 56.11 | 273.3 | | 0.522 | 2.225 | 1.92 | 0.45 |
| Stage 6 | 56.19 | 266.1 | | 0.070 | 0.533 | **14.29** | **1.88** |
| Stage 7 | 56.29 | 265.6 | 0.0080 | 0.087 | 0.037 | **11.49** | **27.03** |
| **Process** | **56.29** | **265.6** | | **1.506** | **9.624** | | |

Figure 9 shows the brightness Z-factor and ERIC Z-factor weighted brightness gains and ERIC reductions for the 15 experiments conducted. Because the Z-factor weighted brightness gain and ERIC reduction take fiber loss into consideration, we can easily determine that experiments 7 and 14 gave the best deinking performance without examining the fiber loss data. Recall that the final brightness Z-factor is about unit value and the ERIC Z-factor is about 10 units, so the ISO brightness for experiment 9 may be on the low side even though it gave good ERIC reduction.

To validate the determined best flotation (experiments 7 and 14). we plotted the corresponding ISO brightness gain, ordinary ERIC reduction, and fiber loss for the 15 experiments reported in Fig. 9. As shown in Figure 10, experiments 7 and 14 indeed gave the best performance in terms of both ink removal and fiber yield. Some experiments were not considered optimal because of low brightness gain (experiments 5 and 9). whereas others resulted in high fiber loss (experiments 6, 10, 11, and 15). In summary, Z-factor weighted brightness gain and ERIC reduction are good indicators of deinking performance that also take fiber yield into consideration.

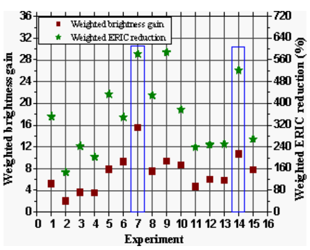


**Fig. 9 Z-factor weighted brightness gain and ERIC reduction of 15 experiments.**

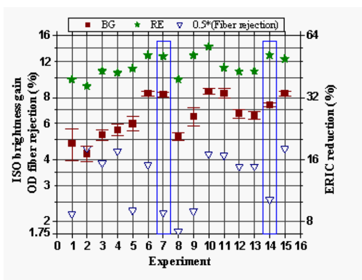


**Fig.** 10 **ISO brightness gain, ERIC reduction, and fiber rejection loss of experiments reported in Fig.** 9.

## CONCLUSIONS

This study defined a deinking selectivity, or Z-factor. for determining deinking performance. The pilot-scale flotation deinking experiments indicate that the Z-factor weighted brightness gain and ERIC reduction have relevance to ISO brightness and ordinary ERIC reduction and are good indicators of deinking process performance. The period or stage Z-factors are good indicators of the efficiency of the periods or stages of a deinking process. A simple criterion associated with the period or stage Z-factor was developed in this study and applied to both pilot-scale experiments and an industrial recycling mill operation for determining the economics of a given period or stage in flotation deinking operations. Therefore, the deinking selectivity concept defined in this study is useful and has economic importance in deinking operations.

## ACKNOWLEDGEMENTS

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