The Application of Mineral Processing Techniques to the Scrap Recycling Industry

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ABSTRACT

The scrap metal recycling industry is a growing industry that plays an important role in the sustainability of a large global metal supply. Unfortunately, recycling lacks many standards, and test procedures in place for mineral processing. These standards and practices, if used in recycling, could aid recyclers in determining and achieving optimal separations for their plant.. New regulations for scrap imports into China make it difficult to obtain the metal recoveries that have been achieved in the past. In order to help scrap yards adhere to the new regulations the Eriez RCS eddy current separator system was tested in full scale. The principles this system uses, called circuit analysis, have been used by the mining industry for years, and can be used with any separation system. The Eriez RCS system surpassed the requirements of the Chinese regulations, while simultaneously increasing the recovery of metals. In order to further analyze eddy current separator circuits, tree analysis was attempted for single eddy current separators, as well as more complex circuits mimicked using locked cycle tests. The circuits used in the locked cycle test were a rougher-cleaner, a rougher-scavenger, and a rougher-cleaner-scavenger. It was found that it is possible to use tree analysis to compare different eddy current separator circuits using the same settings, however standards for this practice need to be established for it to be useful. Using the data analysis methods developed for this particular tree analysis, the rougher-cleaner-scavenger test had the best performance overall. This is the same result as the full scale testing done on the Eriez RCS system, but more testing should be conducted to confirm the data analysis techniques of calculating theoretical efficiency, recovery efficiency, and rejection efficiency.

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CHAPTER 1: INTRODUCTION

1.1 SCRAP METAL RECYCLING TODAY

Recycling is defined as the reuse of a material to make a new product. Scrap metal recycling has been around for hundreds of years. In the beginnings of the scrap metal industry, of modern times, entrepreneurs would sort through material in dumps or refuse piles in order to identify and separate valuable metals that they could then resell (Minter 2013). These early days sound similar to the early days of coal processing, except today many components of a modern scrap yard are still handpicked from the material flow, including circuit boards (Figure 1.1), and the copper from shredded electric motors, also known as meatballs.

Fig 1.1: Circuit boards, all separated by hand.

While some materials are still separated by hand today, most material is separated by a variety machines used to make iron, aluminum, and stainless steel products (Vishesh et. al. 2009). After material is shredded, it is then processed using large magnets that remove ferrous particles. The resulting non-ferrous (NF) residue is then sized and sent to the non-ferrous plant. In the non-ferrous plant eddy current separators separate a mixture of aluminum, copper, zinc, magnesium, lead, and brass as a product that is termed “zorba” by the industry (Figure 1.2). The tailings from the eddy current separator circuit still contain stainless steel, among other poor conducting metals, and some copper, and it is sent to a circuit of sensor sorters. Sensor sorters use either optical, x-ray, or metal detection in order to sense a piece of metal on the belt of the machine and eject it from the stream either using paddles or bursts of air. In a standard American Configuration the tailings from this process are then landfilled, however other countries, particularly countries in the EU, are required by law to landfill only a small percentage of the car being recycled (Vishesh 2009). If this is the case, there will be further processing to remove plastics, glass, and rock.

Fig. 1.2: Zorba from an eddy current separator. Currency shown for scale.

Zorba produced in the United States is primarily sent to China and India for separation into different types of metal by hand, and is then sold to manufacturers as a raw material. Businesses in these countries prefer to buy mixed scrap metals, instead of pure metals, for import, not only because labor is cheap for the separation by hand, but in order to avoid higher taxes for a more valuable, pure product (Minter 2013). Sometimes zorba may be processed by dense medium separation if the final metal products are going to be used in U.S. manufacturing.

The research in this paper was only conducted with the eddy current separators. Although the methods outlined could be used with any separation process, eddy current separators were studied because the NF part of the scrap yard drives the profitability of the shredder (Taylor 1999). Along with the importance of NF metals recovery, China, a major importer of American scrap, recently has enacted laws limiting the metals purity of imported mixed metals at 98%. This law, referred to by American industry as “Operation Green Fence”, means that scrap yards will have to create higher-grade products for their customers, and recovering less metal by making these adjustments.

There are many difficult obstacles for a process engineer working in scrap metals to overcome. Along with the low technology practice of handpicking materials, assaying is done by hand, is not standardized, the quality of the assay varies from person to person. Also, business is conducted from the results of the hand assay. Samples are taken frequently, but can often be too small due to the labor intensive nature of the hand assay procedure. Terms important to processing are sometimes used incorrectly. The terms of recovery, yield, and grade are sometimes used interchangeably by staff working at yards. Terms such as partition curve, micropricing, and tree analysis are rarely used, and these methods are difficult to apply to recycling. The "Green Fence" now in place makes the analysis of a scrap yard by a process engineer more important today, than ever.

1.2 EDDY CURRENT SEPARATORS

An eddy current separator is used to separate nonferrous, conductive metals. There are a few mechanisms of an eddy current separator that can be adjusted in order to make a better or worse separation. The main components of an eddy current separator are the belt, a magnetic rotor at the end of the belt, and a splitter that separates material based on trajectory. A sketch of these components, and how the work together, is shown below in Figure 1.3, which also shows the collection of ferrous fines. Eddy current separators that sort fines frequently have a way to collect ferrous dust that is not separated earlier upstream by large drum magnets.

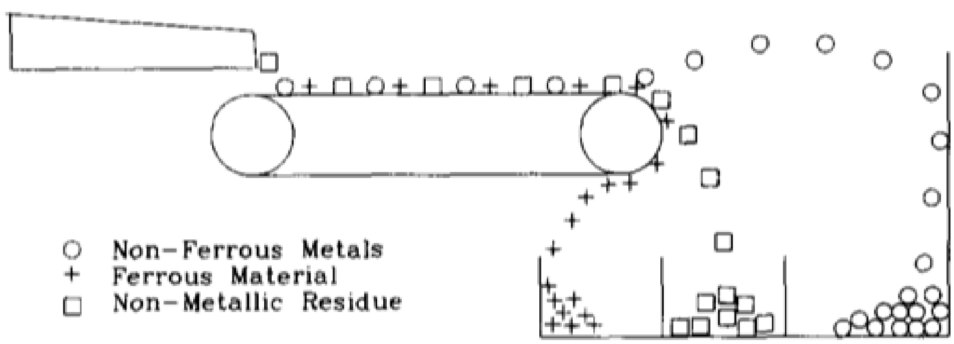


Fig. 1.3: A separation by an eddy current separator (Wilson et. al. 1994).

The belt speed of the eddy current separator influences the velocity in the x direction of particles leaving the belt, and therefore can change the quality of the separation. When a particle leaves the belt, its velocity due to belt speed is affected by centrifugal force (Zhang et. al. 1999). An equation for the centrifugal force of a particle at the end of a belt is shown in Figure 1.4, where L is the length of the particle, W is the width of the particle, T is the thickness of the particle, ρ is the density of the particle, R is the radius of the external shell at the end of the belt, and ω is the angular velocity of the particle.

$$F_c = LWT\rho R\omega^2$$

Fig. 1.4: Equation for centrifugal force perpendicular to the shell surface.

The other mechanism that affects a particles trajectory is the magnetic field created by the rotor contained within the shell at the end of the belt of the eddy current separator. The rotor is composed of alternating magnets as shown in Figure 1.5. The alternating magnets, when the rotor is spinning at a high frequency, creates eddy currents within a conductive particle and cause it to be ejected from the other material.

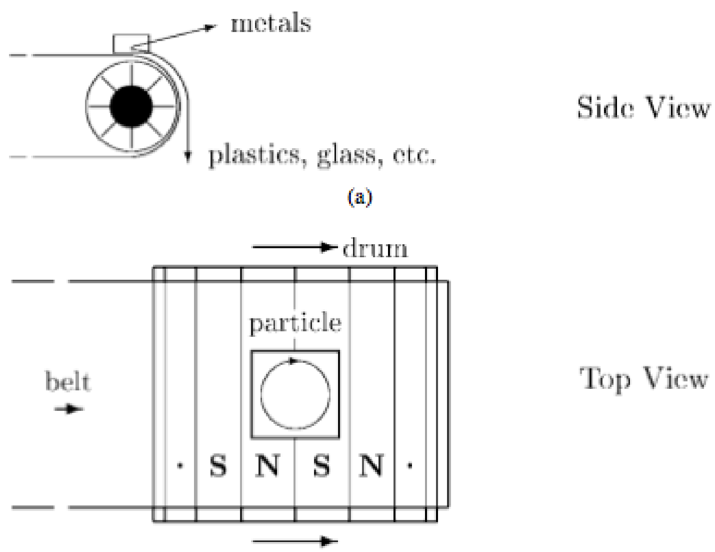


Fig 1.5: Magnetic rotor causing eddy currents to be induced in conductive particles (Rem et. al. 1997)

The interaction between the eddy currents in conductive particles and the magnetic field is called the Lorentz force (Rem et. al. 1997). An eddy current is essentially a current moving through the particle in a loop, and this current is both induced and interacts with the fluctuating magnetic field created by the rotor spinning at a high frequency. This interaction is difficult to model, however it is possible to approximate the force on the particle due to the magnetic field. An equation for this force is shown in Figure 1.6., where K is a complex coefficient related to magnetic roll system design, B_e is the effective magnetic induction, f is the oscillation frequency of the magnetic field, m is the mass of the particle, σ is the conductivity of the particle, ρ is the density of the particle, and p is a coefficient related to shape and orientation.

$$F_d = KB_e^2 f m \frac{\sigma}{\rho} p$$

Fig 1.6: Equation for deflection due to magnetic field (Zhang et. al. 1999).

Effective magnetic induction can be affected by the number of poles around the circumference of the rotor as well as the radius of the rotor. Other forces acting on the particles include frictional forces, drag forces, gravitational forces, and interparticle forces. A diagram showing the forces acting on a particle while in the eddy current field is shown in Figure 1.7.

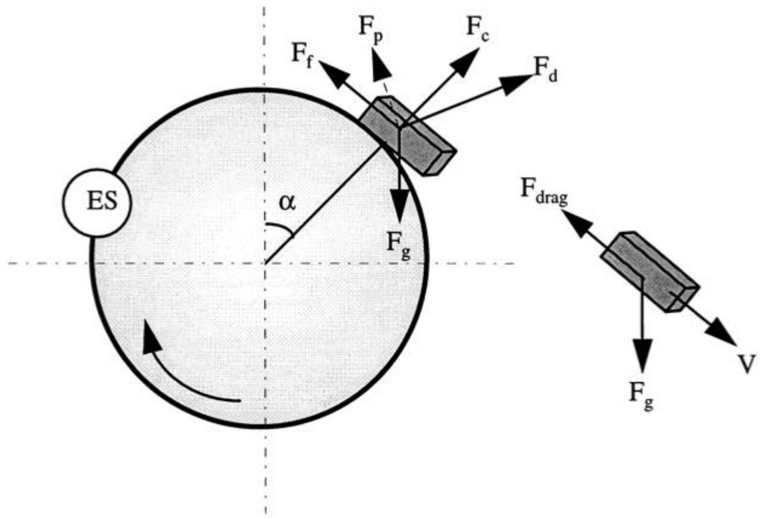


Fig 1.7: Force diagram for an airborne particle and a particle about to leave the belt (Zhang et. al. 1999).

After the particle is airborne it will fall into one of two collection bins. The material that reports to each bin can be changed by moving a splitter. A splitter is a blade that can be adjusted for angle and possibly moved in the x and y direction depending on the maker of the machine. The splitter allows for separation based on trajectory of the particle. A splitter is shown in the schematic in Figure 1.8 labeled as number 4.

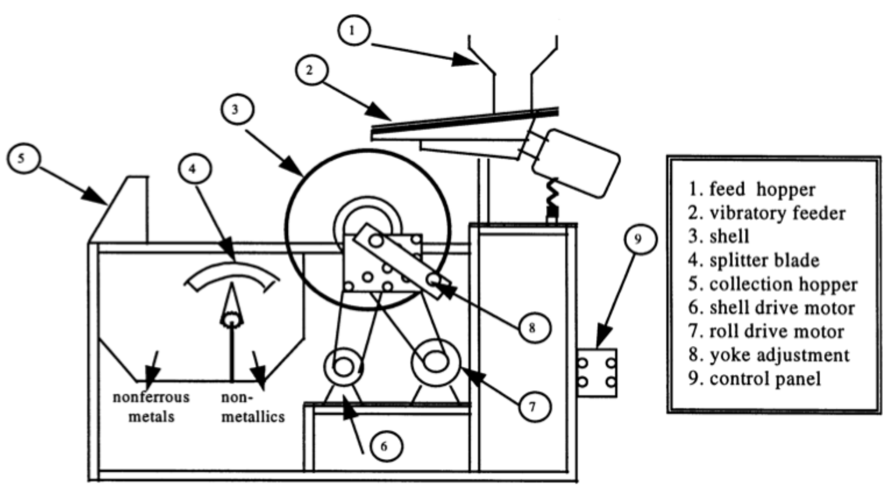


Fig 1.8: A sketch of an eddy current separator also showing a splitter (Zhang et. al. 1999)

There are many factors that determine if a particle reports to the correct fraction while being processed by an eddy current separator. Factors that may not be so obvious and cause misplacement are liberation and particle size. Particles not fully liberated may not receive the full effects of the magnetic field. Smaller conductive particles may not have enough momentum in the x direction, or be affected enough by the magnetic field to make it over the splitter.

1.3 PROCESS CALCULATIONS

In order to track the performance of a scrap yard over time, it is important to be able to so some basic process calculations. These calculations can also be used to justify adding new separation equipment, which is a decision that must be made carefully in tough economic times. The calculations illustrated below can help an operator make better decisions regarding equipment purchases and scrap sales, as well as increasing communication regarding efficiency to employees and other scrap yards.

Figure 1.9 shows a sample that has been fed into an eddy current separator. Although the ratio of metals to waste is above average, this hypothetical sample has been chosen to simplify calculations. This feed sample contains twelve blocks of equal weight. The four silver blocks are pure aluminum, the four red-orange blocks are pure copper, and the four black blocks are plastic. When separated, the blocks shown on the red background go under the splitter of the eddy current separator and are sent to a landfill, while the blocks on the green background go over the splitter and report to the zorba product.

Fig 1.9: Feed sample showing split by eddy current separator.

1.3.1 YIELD

The most common measure of separation performance is yield. Yield is simply the mass percentage of feed that ends up in a separated product, Most commonly, yield is used to describe the fraction that is more valuable (i.e., zorba yield). In Figures 1.9 and 1.10, zorba yield is indicated as the area within the green background. Note that this area contains both desirable metals and unwanted misplaced plastic. Because the blocks in the diagram are equal in weight, the yield for both fractions is 50%. A yield describing the material that will be sold as zorba is calculated by:

$$Yield\ (\%) = 100 \times \frac{Mass\ of\ Concentrate}{Mass\ of\ Feed}$$

$$Yield\ (\%) = 100 \times \frac{6\ Blocks}{12\ Blocks} = 50\%$$

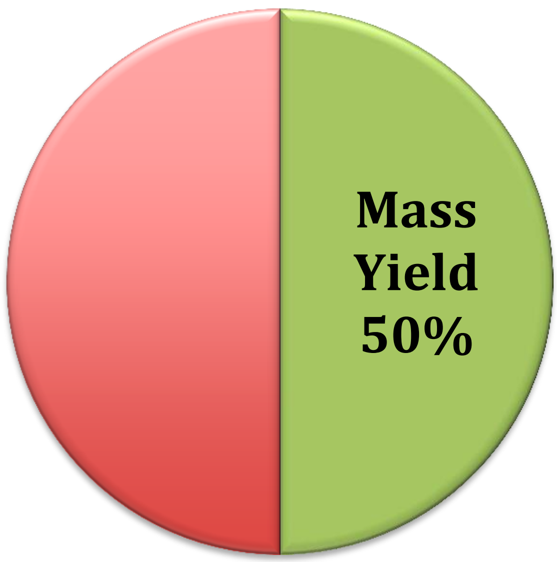


Fig. 1.10: Graphical result of a yield calculation.

A sudden change in yield can be caused by changes in feed composition or by an equipment malfunction that impacts separation performance.

1.3.2 RECOVERY AND REJECTION

Fig. 1.11: Illustration of material used to calculate recovery and rejection of zorba.

Recovery and rejection calculations are used to show the distribution of a specific component present in the feed between the separated products. These parameters are important for assessing the overall performance of the process. For process engineers, both recovery and rejection measurements are better indicators of separation performance than yield or the metals content in the waste of a process. For example, the valuable metal blocks that have been "recovered" are shown in the green area on Figure 1.11 and 1.12. Zorba recovery, which is the percentage of recovered metals out of the total metals in the feed, is calculated as:

$$Zorba\ Recovery\ (\%) = 100 \times \frac{Mass\ of\ zorba\ metals\ in\ the\ concentrate}{Mass\ of\ zorba\ metals\ in\ the\ feed}$$

$$Zorba\ Recovery = 100 \times \frac{5\ Blocks}{8\ Blocks} = 63\%$$

Thus, for every 100 tons of metals sent to the separator, 63 tons were recovered as valuable zorba product. The remaining 38 tons were lost to the waste stream.

The 38 tons of metals that were lost can be described by rejection. Rejection is the opposite of recovery. Rejection is normally used to quantify the percentage of a specific type of material that reported to the waste stream in a separation process. In the current example, the blocks in the red area of Figure 1.11 represent those that reported to the waste stream. As such, zorba metals rejection is calculated as:

$$Zorba\ Rejection = 100\% - Recovery = 100 \times \frac{Mass\ of\ zorba\ metals\ in\ the\ tailings}{Mass\ of\ zorba\ metals\ in\ the\ feed}$$

$$Zorba\ Rejection = 100\% - 62\% = 100 \times \frac{3\ Blocks}{8\ Blocks} = 38\%$$

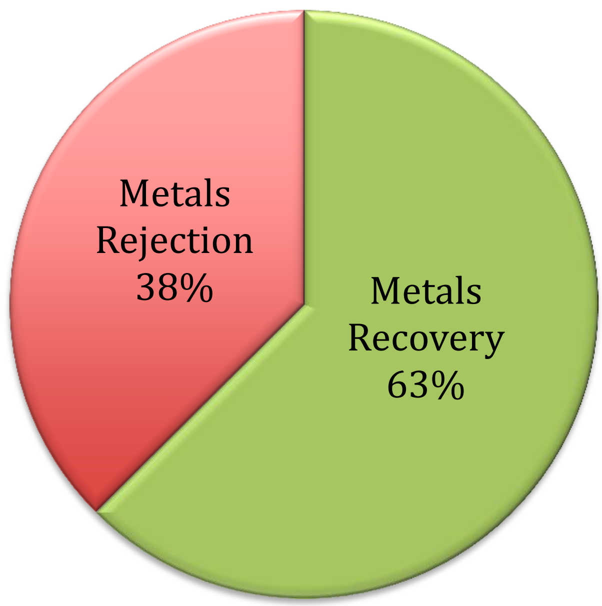


Fig. 1.12: Graphical interpretation of how recovery and rejection contribute to the feed as a whole.

In this case the metals rejection is shown as the red area in both the pie chart and the material diagram. Once again the shaded area, which represents plastic, is not used in the calculation for rejection or recovery of metals. However, rejection can also be used to describe the amount of plastic that ends up in the zorba, and would help to describe the amount of contamination in the product. Therefore designing a process with a higher plastic rejection could mean a higher grade zorba product. Recovery and rejection are also useful for determining metal losses per hour, which then can be converted into revenue losses using current market prices.

1.3.3 GRADE

Grade describes the amount of a specific constituent present in a scrap sample, i.e., product purity. The grade of a pile of scrap is important for both sales and processing calculations. The blocks in the non-shaded concentrate region shown in Figure 1.13 are used to calculate the grade of the zorba. Of the non-shaded blocks, 50 percent of them are aluminum, making the grade of the zorba produced in this process 50% aluminum. If indicated, the grade can also describe the overall metals content, which is the sum of the grade of aluminum and the grade of copper. Aluminum grade is calculated as shown below:

$$Aluminum\ Grade = 100\ \times \frac{Mass\ of\ aluminum\ in\ concentrate}{Total\ mass\ of\ concentrate}$$

$$Aluminum\ Grade = 100 \times \frac{3\ Blocks\ of\ Al}{3\ Blocks\ of\ Al + 2\ Blocks\ of\ Cu + 1\ Block\ of\ Plastic} = 50\%$$

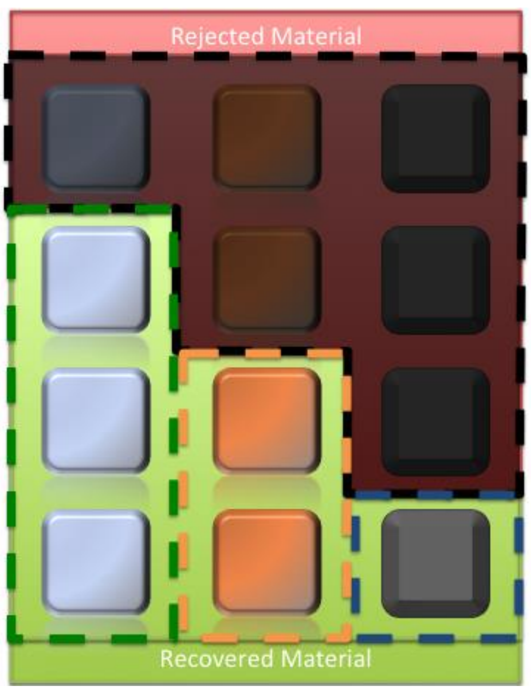


Figure 1.13: How the recovered material is categorized for grade calculations.

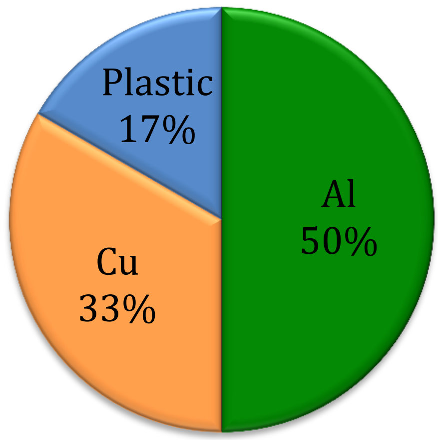


Fig. 1.14: Graphical interpretation of the zorba grade calculation.

Grade can also describe the metal content in the feed and waste streams from a separator. Therefore, waste grade is also an important parameter for monitoring metal losses.

1.3.4 SEPARATION EFFICENCY

Separation efficiency is a technical metric that shows the overall effectiveness of the separation. For the current example, separation efficiency would typically be reported as the recovery of metals in the zorba product minus the recovery of plastic in the metals product. Separation efficiency can be calculated as:

$$Separation\ Efficiency = Zorba\ Metals\ Recovery - Plastic\ Recovery$$

$$Separation\ Efficiency = 63\% - 25\% = 38\%$$

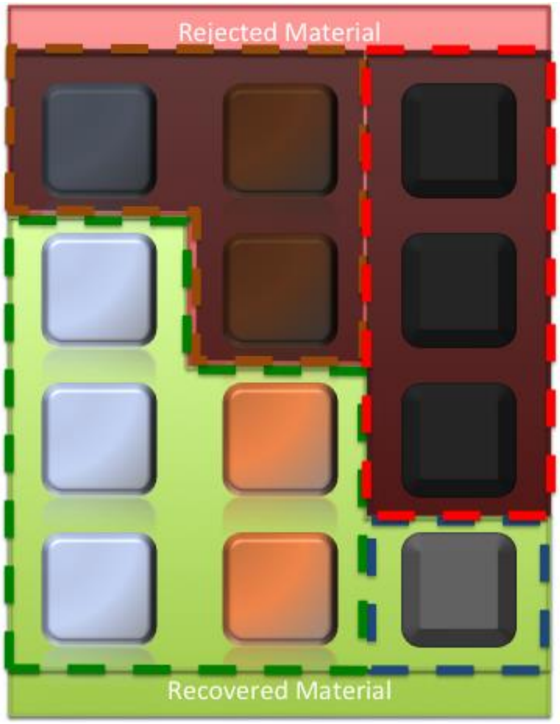


Fig. 1.15: Split showing only recovery of materials is used to calculate separation efficiency.

Figure 1.15 shows both the recovery and rejection of plastic and metals, and the dotted lines in the figure are color coded to the separation efficiency equation. Only the recovery of plastic and the recovery of metals are used in the calculation. Rejection, which describes the distribution of material to the shaded area, is not used.

1.3.5 USING YIELD AND RECOVERY

While yield's simple calculation does not involve measuring grade, it is not the best indicator of separation performance. Since recovery and rejection describe the percent of metals that reach the customer, it is a much better indication of how well the separation is performing and if improvements can be made. In the example shown below in Figure 1.16, the feed composition and how the material splits changes; yet the yield stays the same, making yield a poor indicator of separation performance.

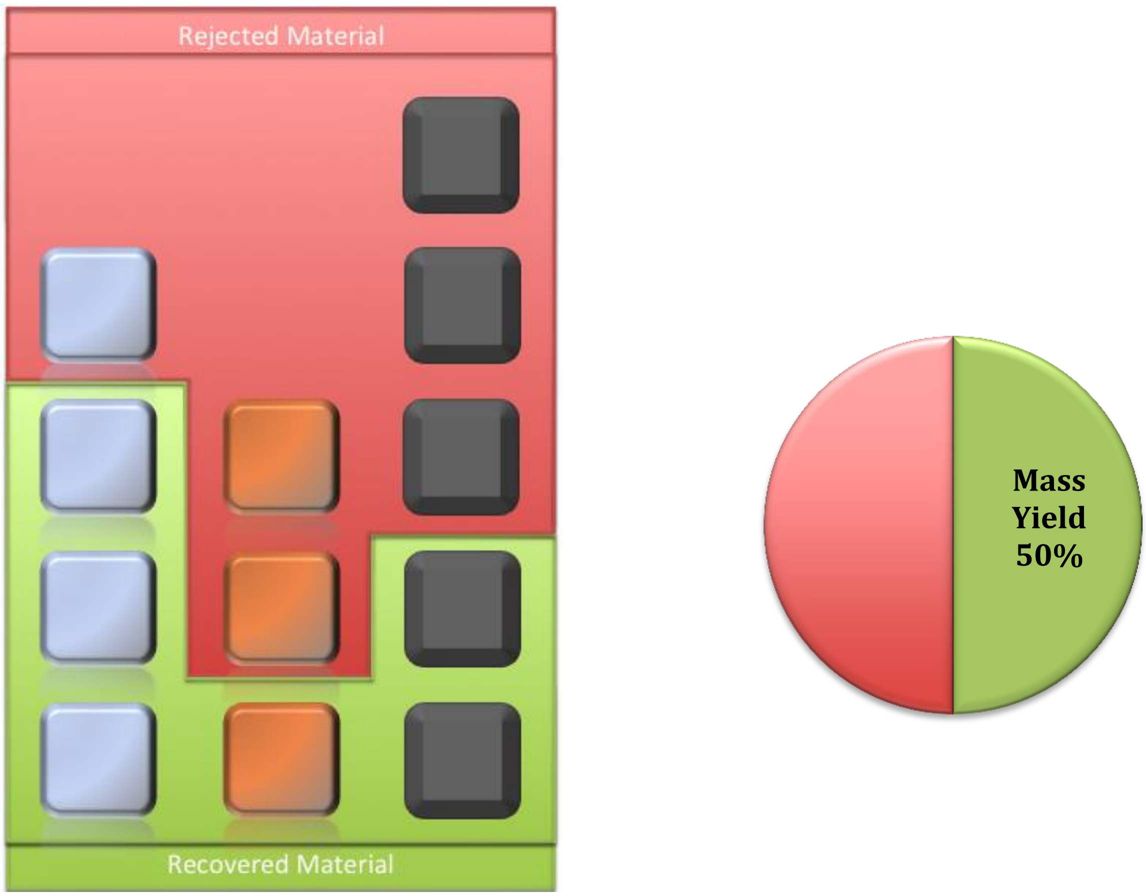
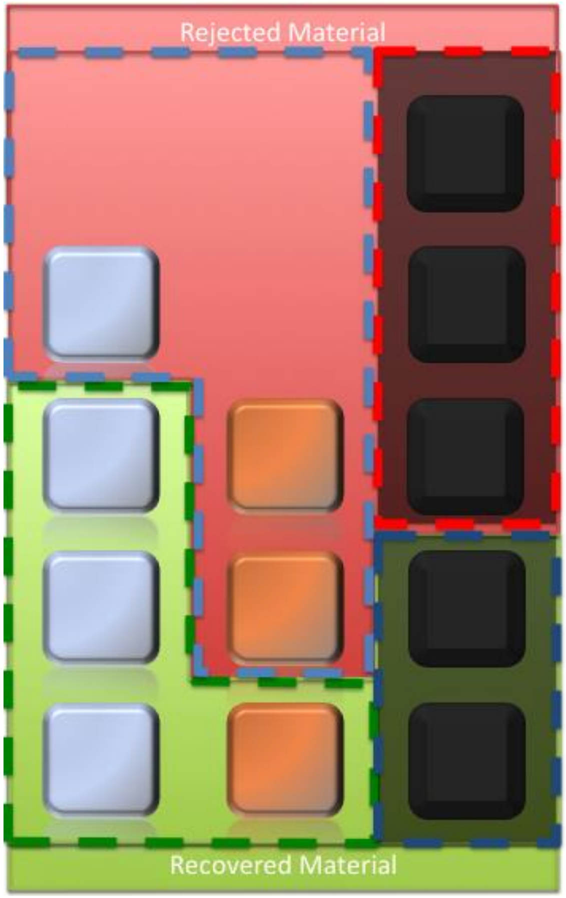


Fig. 1.16: Visual and graphical interpretation of the mass yield of a different feed.

As shown in the pie chart in Figure 1.16, the yield for the changed feed is still 50%. However, in Figure 1.17 it is apparent that the metals recovery has dropped from 63% to 57%, and the overall separation efficiency has dropped from 38% to 17%. Copper was the only metal where the recovery dropped: dropping from 50% to 33%. With copper being the more valuable metal, this drop in recovery would create a problem for the processor. If only yield is measured and grade measurements are not completed consistently, the processor may not be aware in the drop in performance. This drop in recovery can also be an indicator of a change in shape of the material, possibly indicating poor shredder performance, a problem with sizing, or the separators themselves.



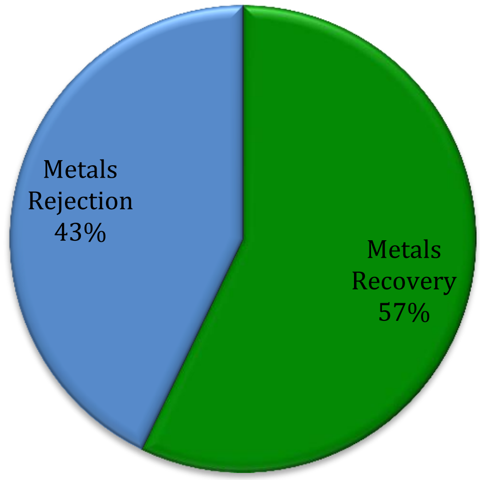


Fig. 1.17: Visual and graphical interpretation of recovery and rejection for a different feed.

A 5% loss in metals recovery can have a large effect over time. If a scrap yard runs only 1/4 of a ton per hour of copper through eddy current separators, and the copper recovery drops by 17%, that is the equivalent of losing 476,000 lb of copper every year if the separators are in operation 16 hours a day for 50 weeks out of the year. Knowing these numbers, and how to use them, lets the processor know where to look to get every last penny out of their scrap.

1.4 GOALS OF RESEARCH

The goal of this research and this thesis paper is to help start an improvement in the way recycling is done today.

This could be in terms of:

- Product design for future separation.
- Improvements in software used to monitor scrap yards.
- More standard practices, including standards in assaying and testing.
- An understanding of actual metal losses.
- An understanding of what testing could be done next.

,among many other possibilities.

REFERENCES

1. Minter, Adam. Junkyard Planet: Travels in the Billion-dollar Trash Trade. New York: Bloomsbury, 2013.

2. Recycling Today Staff, ISRI Convention: China's Green Fence. Recycling Today, April 23, 2013.

3. Rem, P. C., P. A. Leest, and A. J. Van den Akker. "A model for eddy current separation." *International journal of mineral processing* 49, no. 3 (1997): 193-200.

4. Taylor, B., Providing the profits. Recycling Today, August 1999.

5. Vishesh Kumar, John W. Sutherland, Development and assessment of strategies to ensure economic sustainability of the U.S. automotive recovery infrastructure, Resources, Conservation and Recycling, Volume 53, Issue 8, June 2009, Pages 470-477, ISSN 0921-3449, http://dx.doi.org/10.1016/j.resconrec.2009.03.012.

6. Wilson, R.J., T.J. Veasey, D.M. Squires, The application of mineral processing techniques for the recovery of metal from post-consumer wastes, Minerals Engineering, Volume 7, Issue 8, August 1994, Pages 975-984, ISSN 0892-6875, http://dx.doi.org/10.1016/0892-6875(94)90027-2.

7. Zhang, S., E. Forssberg, B. Arvidson, W. Moss, (1999). Separation mechanisms and criteria of a rotating eddy-current separator operation.*Resources, conservation and recycling*, *25*(3), 215-232.

CHAPTER 2: CIRCUIT ANALYSIS AND TESTING THE ERIEZ RCS SYSTEM

ABSTRACT

Eddy current separators are commonly used in the recycling industry to recover non-ferrous metals from nonmetallic waste residues. Recently, the push for higher grade products from market consumers has created an incentive for designers to improve the separation efficiency of these machines. In response to this challenge, a new multi-stage eddy current separator has been developed based on a fundamental concept developed in process engineering. Production runs conducted with a full-scale industrial machine showed that this new technology could readily generate zorba products with purity levels exceeding 98% metals while maintaining mass recoveries of metals in excess of 95%. As such, this new technology makes it possible for plant operators to meet increasingly stringent purity targets desired by customers, while also improving profitability by increasing the amounts of metals recovered from wastes.

2.1 INTRODUCTION

Production statistics compiled by the Institute of Scrap Recycling Industries (ISRI) indicate that in 2014 the scrap recycling industry in the United States annually processes more than 113 million metric tons of scrap, including 74 million metric tons of ferrous scrap and 8 million metric tons of nonferrous scrap. Recyclable metals present in the nonferrous scrap include many high-value “zorba” metals such as aluminum, brass, copper, nickel and zinc. Since these non-ferrous metals do not respond to magnetic separations, they are often recovered using dense medium (float-sink) processes that require wetting/dewatering of the scrap feedstock. Scrap yard operators may also elect to sell their Zorba products to foreign contractors whose lower pay scales permit labor-intensive manual sorting (handpicking) to be economically viable. However, this approach usually does not provide the scrap yard operator with the largest financial return on their saleable products.

An attractive option for sorting nonferrous metals from waste is eddy current separation (Zhang et al., 1999). As shown in Figure 2.1, an ECS machine consists of a rotor encompassed by a shell made of magnets with alternating magnetic poles, which is contained inside a conveyor belt drum. When rotated at high speed, the rotor induces eddy currents within nonmagnetic, conductive metals. The induced field deflects nonferrous metals up and away from the conveyor drum, while non-metallic materials remain unaffected by the field and simply drop from the end of the conveyor. During operation, nonferrous metals and nonmetallic waste is fed onto the conveyor belt in a thin layer. The belt then passes over the rotor, where the induced

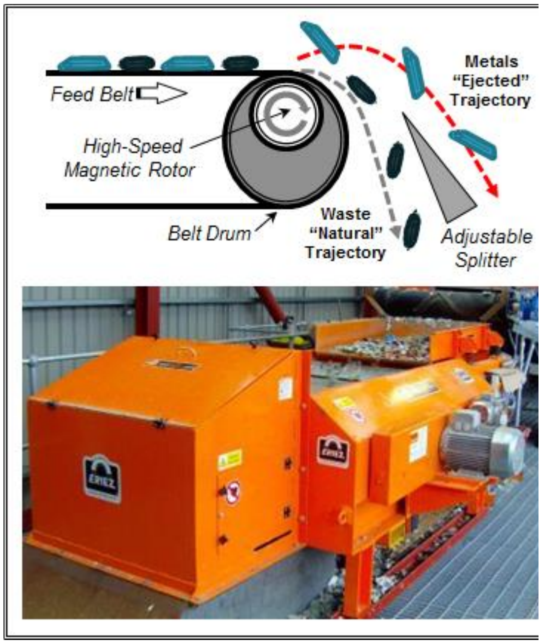


Fig. 2.1. Eddy current separator (ECS).

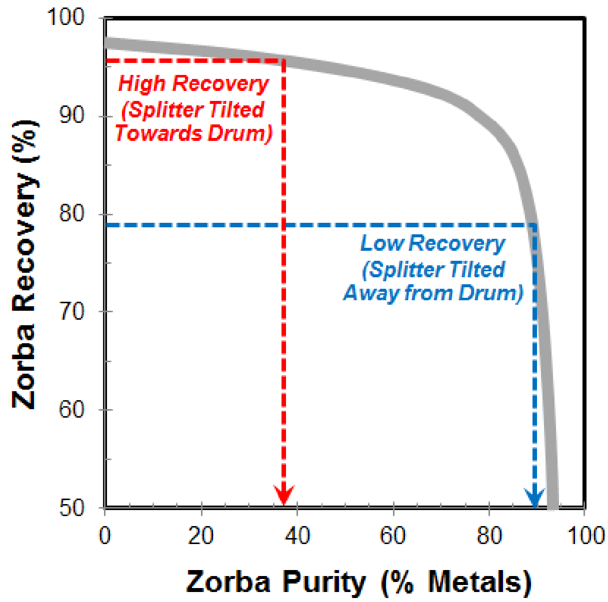


Fig. 2.2. Example of recovery vs. purity trade-off.

eddy currents cause zorba metals to become repelled from the rotor. The repulsion causes the trajectory of the non-ferrous metal to be different than the nonmetallic contaminants. The two streams of material are separated by an adjustable splitter into metals and non-metals products. The splitter position can either be (i) moved outward to improve the purity of the metals product at the expense of mass recovery or (ii) moved inward to improve the mass recovery at the expense of product purity. The trade-off between product recovery and product quality typically results in the creating of a recovery-grade curve such as that shown in Figure 2.2.

A large financial incentive exists to shift the separation curve towards the right-upper corner of the recovery-grade plot, i.e., towards maximum recovery and maximum purity. This shift is possible by reducing the amount of material that is inadvertently misplaced during an eddy current separation. The misplacement of metals and nonmetals is caused by a wide variety of reasons including the improper orientation of objects entering the eddy current field (Figure 2.3a), interferences created by material contacts (Figure 2.3b), and fouling of splitters as a result of material hang-ups (Figure 2.3c). Whatever the cause, misplacement shifts the recovery-grade curve away from the optimum operating region and adversely impacts product recovery and/or quality.

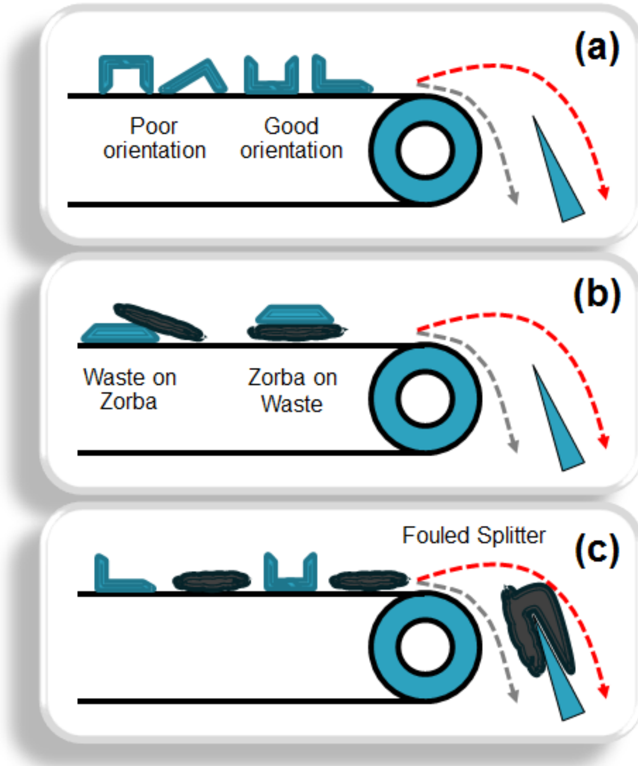


Fig. 2.3. Misplacement mechanisms during eddy current separation. (a) Improper Orientation, (b) Material Interaction, and (c) Splitter Fouling.

In light of the misplacement problem, process engineers from Eriez and Virginia Tech have applied advanced concepts originally developed in the minerals processing industry to develop a next-generation eddy current separator that can provide a higher quality metal product at a higher recovery. This new innovation, called the Eriez RCS eddy current separator, incorporates multiple stages of cleaning (to improve quality) and scavenging (to improve recovery) into a single compact unit. The new design is capable of overcoming the longstanding dilemma created by the trade-off between metals recovery and metals grade that is unavoidable with a single-stage machine.

2.2 TECHNOLOGY DESCRIPTION

It has long been known that multi-stage processing systems can be used to improve the recovery or purity of recycled products. Multi-stage layouts that involve reprocessing of the valuable product to improve purity and reduce contamination are typically called "cleaning circuits." Likewise, layouts that involve reprocessing of the waste product to improve the recovery of valuable components are called "scavenging circuits." Cleaning circuits improve product purity at the expense of recovery, while scavenging circuits improve recovery at the expense of product purity. However, if properly configured, combinations of cleaning and scavenging circuits can be used together to simultaneously improve both product recovery and purity.

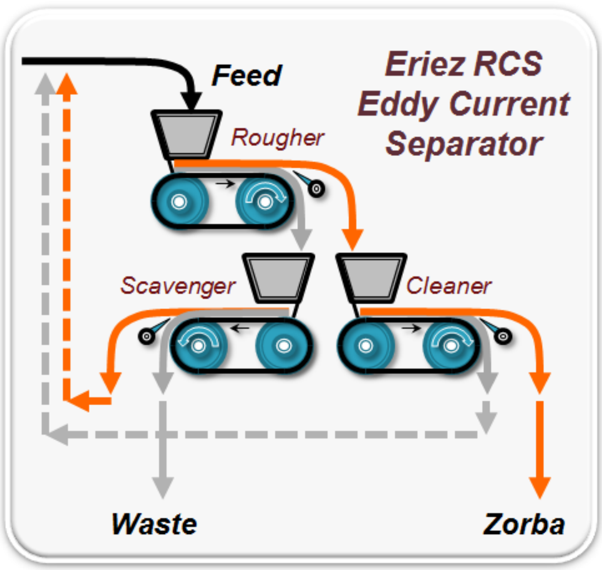


Fig. 2.4. Material flows passing through the three-stage Eriez RCS eddy current separator.

Figure 2.4 provides a simplified schematic of material flows through the new Eriez RCS eddy current separator. During operation, mixed metal/waste scrap is initially passed through a "rougher" stage to sort the feed into metallic and non-metallic products. The metals product from the rougher stage is then passed to a "cleaner" stage of separation to eliminate any nonmetallic waste that may have been misplaced into the saleable product. Likewise, the nonmetallic product from the rougher stage is passed through a "scavenger" stage of separation to recover any metals that may have been accidentally misplaced into the waste stream. These two stages of cleaning and scavenging ensure that little misplaced material is left in either the metals or waste products. The most novel feature of the Eriez RCS machine, however, is the manner in which the off-spec streams (i.e., waste stream from the cleaner unit and off-spec metals stream from the scavenger unit) are further processed. These two off-spec streams are recycled back to the feed of the rougher stage of the Eriez RCS (Rougher-Cleaner-Scavenger) machine. As discussed below, the forced recirculation of off-spec material creates a selfregulating loop of cleaning and scavenging that is superior in terms of separation efficiency compared to any other layout of process units.

2.3 THEORETICAL DISCUSSION

A process engineering tool known as linear circuit analysis (Meloy, 1983) can be used to explain why the new Eriez RCS eddy current separator offers such a high level of separation performance. This powerful tool has been used to design multi-stage circuits for size classification (Honaker et al., 2007), density concentration (Luttrell et al., 1998; McKeon and Luttrell, 2005) and magnetic separation (Luttrell et al., 2004). According to the circuit analysis concept, the tonnage of a particular piece of material reporting to the metal concentrate (C) can be calculated by multiplying the tonnage of the material in the feed (F) by a separation probability (P). Mathematically, this relationship can be defined as:

$$C = P(F) \quad or \quad \frac{C}{F} = P \qquad [1]$$

For the case of perfect separation, valuable metallic objects would have P_{metal}=1 and non-metallic wastes would have P_{waste}=0. Unfortunately, real-world separators suffer from misplacement since some portion of the metals may be lost to waste (P_{metal}<1) and some waste may be inadvertently passed into the metals concentrate (P_{waste}>0). To reduce this misplacement, the Eriez RCS technology reprocesses both the metals concentrate and the non-metals waste as shown in Figure 2.5. The waste rejected from the final metals concentrate and the metals recovered from the final non-metals waste are recycled back to the feed for reprocessing. According to linear circuit analysis, the concentrate (C) produced by the Eriez RCS technology can be calculated as:

$$C = F'P_rP_c \qquad [2]$$

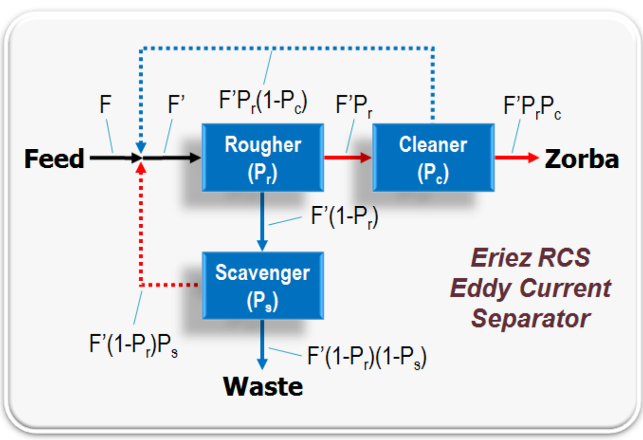


Fig. 2.5. Materials flow for the three-stage Eriez RCS eddy current separation technology.

P_r, P_c and P_s are the separation probabilities for the rougher, cleaner and scavenger stages, respectively. Since two streams are recycled back to the feed (F), the new internal feed (F') passed to the eddy current separators is given by:

$$F = F' - F' P_r (1 - P_c) - F'(1 - P_r) P_s \quad [3]$$

$$F = F'[1 - P_r(1 - P_c) - (1 - P_r) P_s] \quad [4]$$

$$F' = \frac{F}{1 - P_r(1 - P_c) - (1 - P_r) P_s} \quad [5]$$

By combining Equations [2] and [5], the concentrate-to-feed (C/F) ratio for the Eriez ECS technology can be calculated as:

$$C = \left[\frac{F}{1 - P_r(1 - P_c) - (1 - P_r) P_s} \right] P_r P_c \quad [6]$$

$$\frac{C}{F} = \frac{P_r P_c}{1 - P_r(1 - P_c) - (1 - P_r) P_s} \quad [7]$$

If it is assumed that the separation probability (P) is identical for all three separators (i.e., $P=P_r=P_c=P_s$), then Equation [7] simplifies to:

$$\frac{C}{F} = \frac{P^2}{1 - 2P + 2P^2} \quad [8]$$

If a single-stage eddy current separator recovered 90% of the metals (P=0.9) and 10% of the waste (P=0.1), then the three-stage Eriez RCS technology would be expected to give:

$$\textit{Metals in Zorba}: \quad \frac{C}{F} = \frac{P^2}{1 - 2P + 2P^2} = \frac{0.9^2}{1 - 2(0.9) + 2(0.9^2)} = 0.988 \quad [9]$$

$$\textit{Waste in Zorba}: \quad \frac{C}{F} = \frac{P^2}{1 - 2P + 2P^2} = \frac{0.1^2}{1 - 2(0.1) + 2(0.1^2)} = 0.0122 \quad [10]$$

According to this analysis, the Eriez RCS system would reduce the amount of waste recovered in the zorba concentrate from 10% down to only 1.2% (P=0.0122) while simultaneously increasing the amount of metals recovered in the zorba concentrate from 90% to 98.8% (P=0.988). Therefore, the use of three stages of separation coupled with the recirculation of off-spec material back to the feed, the Eriez RCS technology is capable of producing (i) high-purity low-impurity zorba concentrates that are attractive to customers and (ii) higher recoveries and lower losses of metals that can increase the overall profitability of recycling operations.

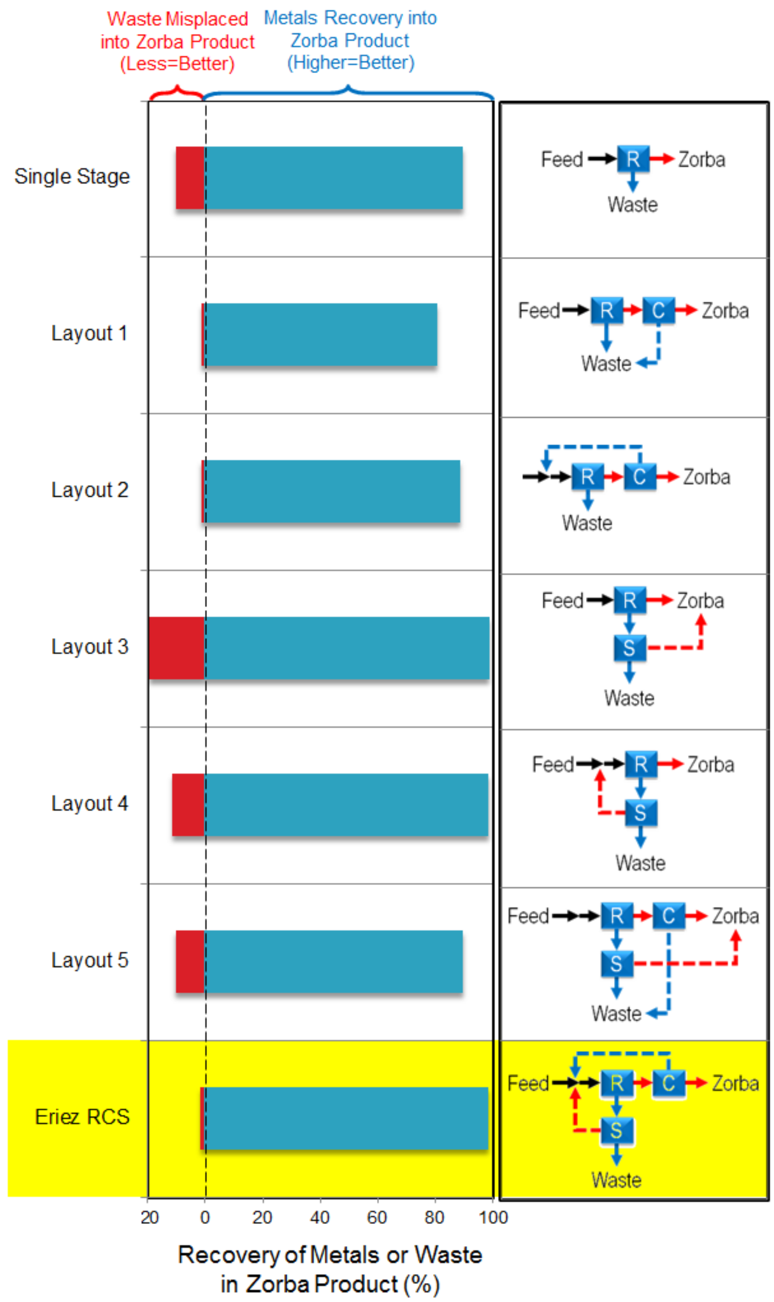


Fig. 2.6. Comparison of misplaced material for different layouts of multi-stage eddy current separators.

Using linear circuit analysis, the recovery of metals and non-metals (waste) in the zorba concentrate can be estimated for several other configurations of two- and three-stage eddy current systems. The comparative results, which are plotted in Figure 2.6, indicate that no other layout is capable of achieving the high-purity and high-recovery performance of the three-stage Eriez RCS technology. Interestingly, the analysis indicates that a three-stage layout without recirculation (Layout 5) would be expected to perform no better than a single-stage unit when the off-spec products are passed forward and recombined with their corresponding metals or waste products. This type of poorly designed layout represents three times the capital investment with no benefit in terms of separation performance.

2.4 FULL SCALE TESTING

In order to fully demonstrate the improved performance capabilities of a multi-stage eddy current separator, a commercial-scale prototype (Eriez RSC Eddy Current Separator) was designed, constructed and tested. The innovative prototype, which is shown in Figure 2.7, made it possible to compare the performance of an integrated “optimal” three-stage machine to that of a single-stage separator. The Eriez RSC machine was tested using a 5 ton batch of automotive shredder residue having an upper particle size of 32 mm (~1¼ inches) and containing 7 to 10% zorba mixed with waste fluff. The RSC machine processed almost 10,000 lb of material during testing. Each set of circuit tests were run with varying feed tonnage rates and splitter settings to provide a wide range of operating conditions and performance values. During testing, representative samples of both waste fluff and concentrate zorba were collected at the same time intervals during the duration of the test until the mass of zorba collected satisfied a minimum sampling requirement of 34 kg (75 pounds) or greater. The zorba concentrate was then hand-sorted to determine the product purity (i.e., percentage of metals in the total zorba product), while the nonmetallic waste was slowly passed over a laboratory-scale eddy current separator to determine the unrecovered metals content. From this data, the zorba purity and mass recovery was calculated.

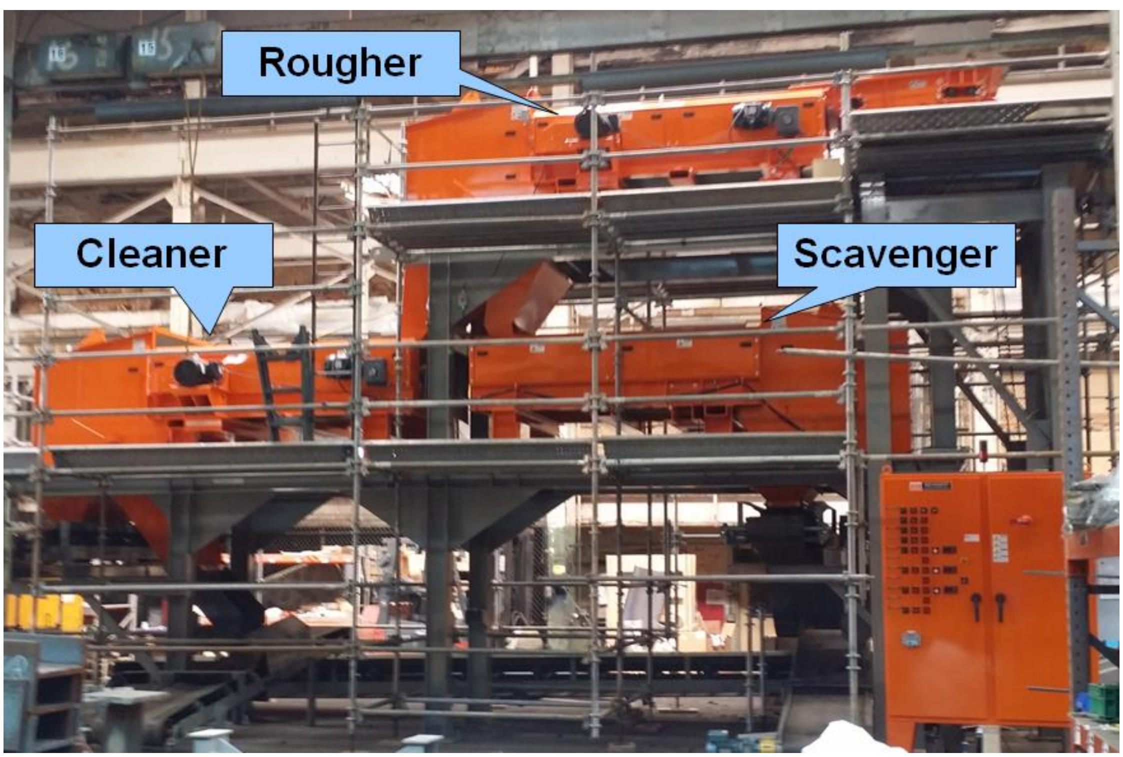


Fig. 2.7. Photograph of the full-scale Eriez RSC eddy current separator.

Figure 2.8 shows recovery-grade curves that compare the performance data collected from the single-stage separator and the three-stage separator. As expected, the separation obtained using the three-stage Eriez RSC machine with recirculation was far superior to that achieved using only the single-stage machine. The single-stage machine, which failed to achieve 98% metals purity, was able to obtain a grade of 93% metals at a recovery of just under 85% by weight during the "best" test run. In contrast, the three-stage Eriez RSC machine easily achieved the target of 98% purity while obtaining metals recoveries of 97-99% by weight. In fact, this high-efficiency machine had to be pushed to abnormal operating conditions for the metal recovery in the zorba product to fall below 90%.

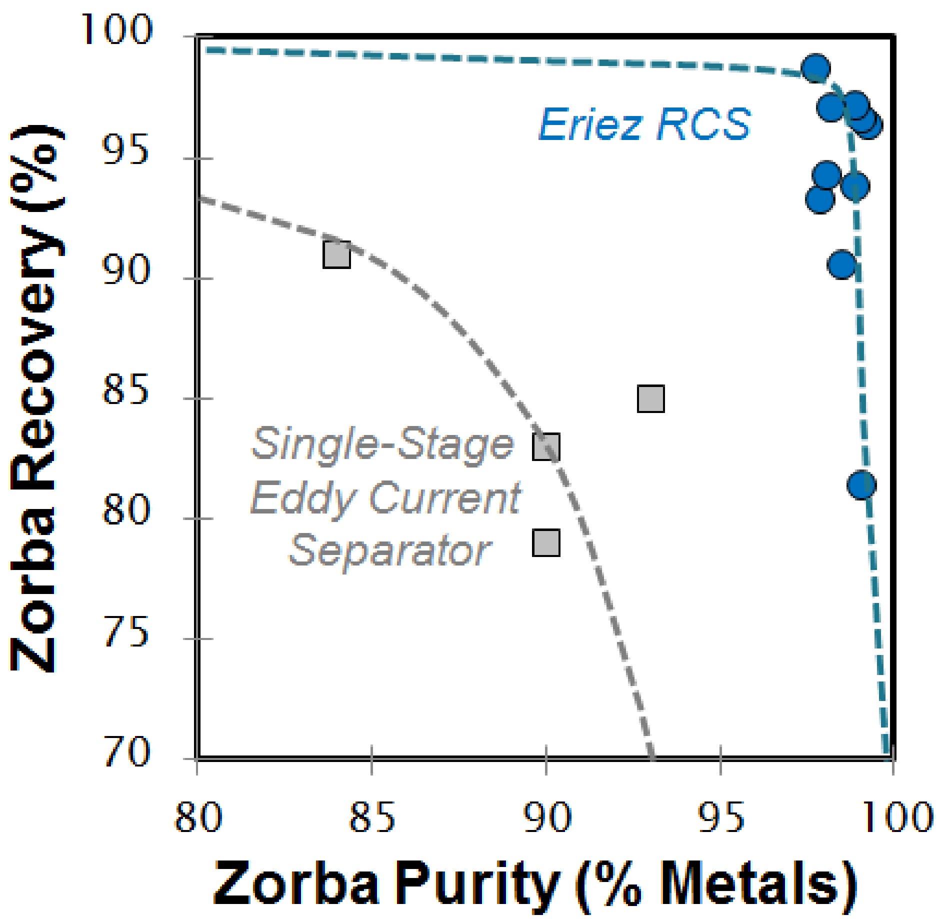


Fig. 2.8. Comparison of separation curves for traditional single-stage and three-stage Eriez RCS eddy current separation technology.

From a business perspective, the three-stage cleaner-scavenger circuit would be expected to offer an attractive payback based on the improved mass yield of metals product. For example, if 13 tons per hour of automotive shredder residue containing 9% zorba metals were fed into a conventional eddy current separator, the single-stage machine has the potential to recover 1.17 tons per hour of pure metals. Using a 98% product grade, the experimental recovery-grade curves shown in Figures 6 and 7 indicate that the single eddy current separator would only recover about 45% of these metals. In contrast, the high-efficiency Eriez RSC machine that incorporates an optimal cleaner-scavenger layout with recirculated secondary streams would recover about 97% of the metals. Therefore, in these two scenarios, the single eddy current separator would generate 0.537 tons per hour of metals compared to 1.16 tons per hour for the three-stage system. Using these values, the Eriez RSC machine would increase zorba output by 116% over the single-stage unit. Assuming a fair market zorba price of $1.50 per kg ($0.68 per lb), and assuming that both systems are run for 40 hours a week for 50 weeks a year, the 116% increase in output for the Eriez RSC machine equates to an additional $1.7 million in annual revenue.

2.5 CONCLUSIONS

A high-efficiency separator, known as the Eriez RCS eddy current separator, has been developed to assist the metals recycling industry in attaining improved levels of separation efficiency. To demonstrate the improved performance of this new technology, a full-scale machine was constructed and tested using a sample of automotive shredder residue containing non-ferrous metals and non-metallic wastes. Full-scale testing of this new machine showed tremendous increases both in the mass recovery of metals and in the purity of the zorba product. The data obtained with the advanced three-stage process indicated that purity levels exceeding 98% metals in the zorba product could be readily obtained at mass recoveries in excess of 95%. The large improvement in separation efficiency was in very good agreement with theoretical predictions obtained using a mathematical engineering tool called linear circuit analysis (Meloy, 1983). The multi-stage machine advocated by this process engineering tool makes it possible for recycling plant operators to meet increasingly stringent purity targets desired by customers, while also improving operator profitability by increasing the amounts of metals recovered from recycled wastes.

REFERENCES

1. Honaker, R.Q., Boaten, F., Shin, D., Luttrell, G.H., 2007. “Evaluation of High-Efficiency Classifying Cyclone Circuits,” Proceedings, SME Annual Meeting and Exhibit, February 25-28, 2007, Denver, Colorado, Preprint 07-143, 7 pp.

2. Luttrell, G.H., Kohmuench, J.N., Stanley, F.L. and Trump, G.D., 1998. “Improving Spiral Performance Using Circuit Analysis,” Minerals and Metallurgical Processing, Vol. 5, No. 4, November 1998, pp. 16-21.

3. Luttrell, G.H., Kohmuench, J.N., and Mankosa, M.J., 2004. “Optimization of Magnetic Separator Circuit Configurations,” SME Annual Meeting, Denver, Colorado, February 24-25, 2004, Preprint 04-90, 5 pp.

4. Meloy, T.P., 1983. “Analysis and Optimization of Mineral Processing and Coal-Cleaning Circuits – Circuit Analysis,” International Journal of Mineral Processing, Vol. 10, p. 61-72.

5. McKeon, T., Luttrell, G.H., 2005. “Application of Linear Circuit Analysis in Gravity Separator Circuit Design” Society for Mining, Metallurgy, and Exploration, 2005. 6 pp.

6. Zhang, S., Forssberg, B.A., Moss, W., 1999. “Separation Mechanisms and Criteria of a Rotating Eddy-Current Separator Operation” Resources, Conservation and Recycling, Vol. 25, No. 3-4, pp. 215-232.

CHAPTER 3: LOCKED CYCLE TESTING AND TREE ANALYSIS

ABSTRACT

Tree analysis and release analysis have been used to analyze the separation of coal from ash in froth flotation circuits for many years. An experiment was developed to determine if the same type of analysis could be used for the separation of zorba metals from automotive shredder residue. For the testing only one separator was available, and a locked cycle testing procedure had to be developed for complex circuits. It was determined that it is possible to compare different circuits processing the same feed using this kind of analysis, however it is important to develop a standardized procedure for assaying and the tree analysis itself for future testing.

3.1 OVERVIEW AND THEORY

In order to gauge how well a separator is performing compared to its optimal operating point it is important to obtain data that helps a process engineer build both grade vs. recovery curves and rejection vs. recovery curves. When it is known how a machine performs compared to the optimum separation for that machine, it is possible to use that data to justify capital expenditures to add units to a separation circuit, or to rearrange circuits.

Tree analysis is a testing method, used in coal flotation, which is used to create a grade recovery boundary for a certain feed coal under certain conditions. In coal flotation testing standards for tree analysis are not always clear, and can sometimes produce different results. According to the paper 'An Evaluation of the Flotation Response of Coals' (Pratten et. al. 1989), several parameters are pertinent to the measurement of flotation response, in regards to release and tree analysis. These parameters are listed below:

1. "A cumulative yield/cumulative ash curve should be able to be constructed from the results of the procedure"
2. "The yield/ash locus must represent the limit of flotation separation."
3. The procedure should be based on a flotation separation instead of another type of separation, such as density.
4. "The results of this procedure should depend solely on the coal and the identity of the flotation reagents used"
5. "The procedure should be used for the entire flotation feed…narrow size fractions can lead to erroneous conclusions…"
6. The procedure should be simple, be able to be performed routinely, and must be repeatable.

Although those parameters are used to describe methods of release analysis and tree analysis in flotation, they can be translated into parameters that can be used for tree analysis using eddy current separators:

1. A cumulative metals yield, cumulative grade curve should be able to be constructed from the results of the procedure.
2. The yield/grade locus must represent the limit of separation.
3. The procedure should be based on the same variables used in eddy current separation.
4. The results of this procedure should depend solely on the contents of the feed and the machine settings.
5. The procedure should be used for the entire feed, not narrow size distributions or individual types of metal.
6. The procedure should be simple, be able to be performed routinely, and must be repeatable.

Tree analysis was the chosen analysis method for this experiment due to its simplicity. In tree flotation a coal feed is floated under certain conditions in a laboratory, and the resulting concentrate and tailings subjected to re-floatation in successive scavenger and cleaner stages (Pratten 1989). This causes the process circuit diagram to branch out, as shown below in Figure 3.1. This diagram of branches is why the procedure is known as tree analysis.

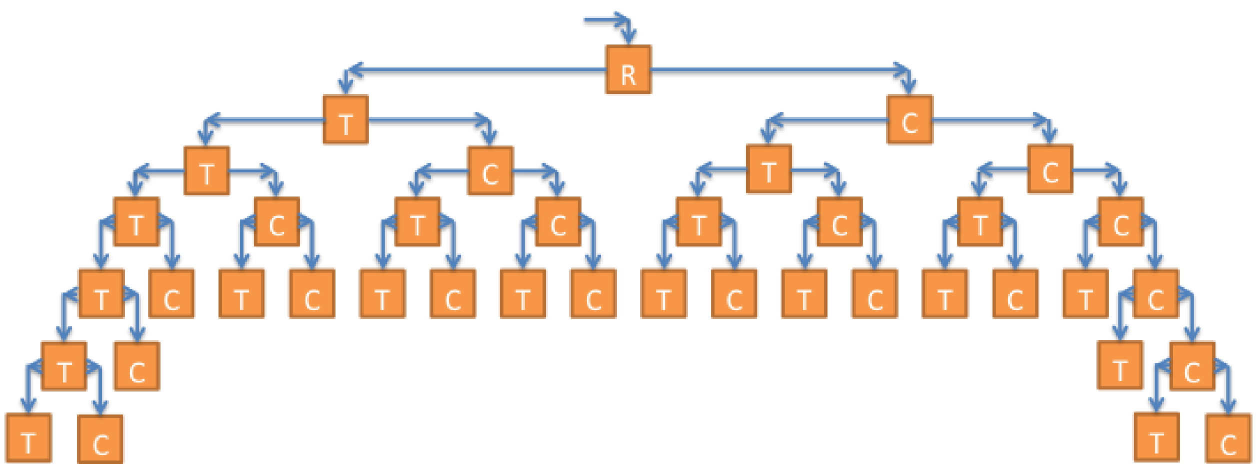


Fig. 3.1 Diagram of tree analysis.

The resulting samples at the bottom of the diagram are assayed and weighed. Then the samples are ordered from the highest grade to the lowest grade. Using this order the cumulative grade of clean coal and the cumulative mass of clean coal are calculated, from the highest grade sample to the lowest grade sample. The cumulative grade and cumulative mass numbers are used as the points for the grade vs. recovery boundary.

The number of levels in a tree analysis has the potential to change the resulting grade vs. recovery boundary, if standards are not put in place. In the paper “Flotation tree analysis – reexamined” it is brought to the readers attention that the number of branches used in the tree analysis, could potentially change the shape of the grade vs. recovery boundary (Meloy et. al 1998). In a model used for the paper Meloy showed how, with a completely liberated coal, the boundary can shift based on the number of levels in the tree. The results of the model are shown below in Figure 3.2. The labels under the curve that read 4, 20, and 100 refer to the amount of levels of the tree analysis.

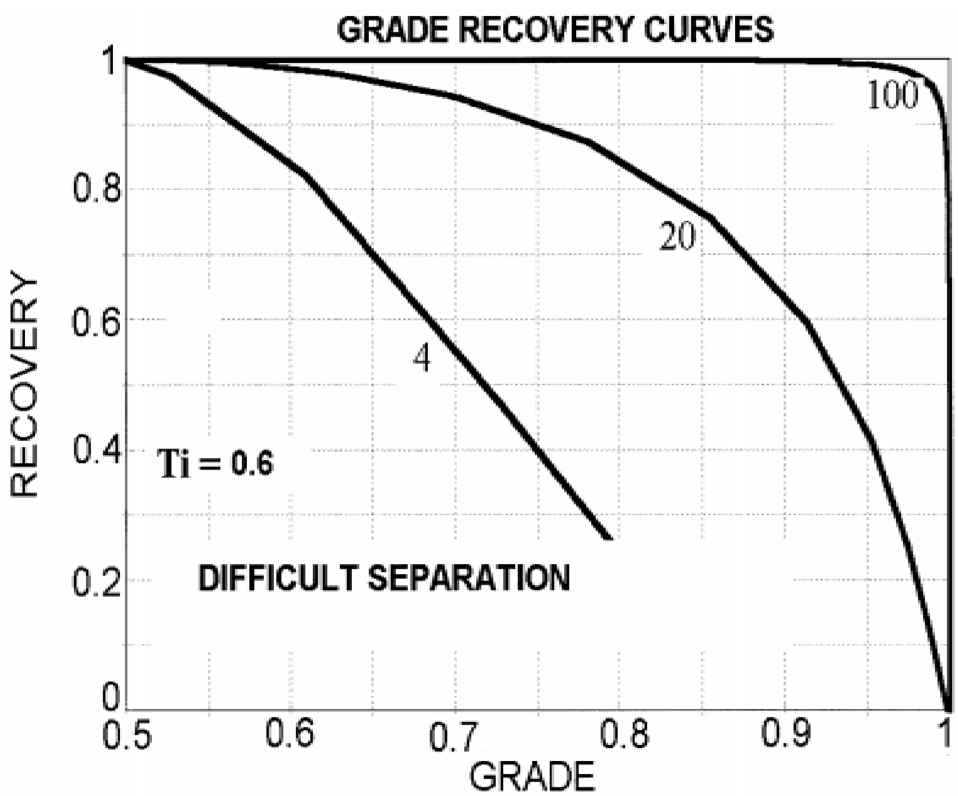


Fig. 3.2 The results from Meloy's model of tree analysis done on a difficult to separate coal (Meloy et. al. 1998)

Although the model used in "Flotation tree analysis - reexamined" lacks complexity it does make a valid point apparent, which is very important for release analysis and the way it would potentially be performed in the recycling industry. In scrap recycling assays are conducted by hand, and a particle that is 51% metal and 49% plastic would most likely be counted as a particle of 100% metal. Essentially assays in the scrap metal recycling industry frequently assume there is complete liberation of metal. Therefore, for a tree analysis of the performance of eddy current separators, it is important to put a constraint on the number of levels used in the procedure.

The paper "Froth flotation: preparation of a laboratory standard" discusses the importance of coming up with and international standard laboratory procedure for both release analysis, and tree analysis (Brown, Hall 1999). The testing in this paper used a standard of re-floating samples until there was no more concentrate produced, or the mass of either the concentrate or tailings of a flotation was less than 5% of the mass of solids in the slurry (Brown, Hall 1999). Although many standards were outlined in Brown's paper, this is the most applicable standard to tree analysis for eddy current separators. Paralllels can be drawn to the standard use of frothers, collectors, and flocculants to the use of specific splitter, and belt speed settings, but before testing these settings were not apparent, and would be different for different machines. Using the known information about tree analysis in coal flotation, an experiment was designed and performed.

This experiment uses locked cycle tests in order to mimic complex circuits. This is necessary in laboratory environments, because it may be difficult or impossible to obtain and arrange the number of separators required for these complex circuits. The locked cycle test allows the technician to mimic circuits that use recirculating loads, when only one machine is available for testing.

3.2 TESTING APPARATUS

For this test, a small eddy current separator was used, similar to the eddy current separator pictured in Figure 3.3.

Fig. 3.3: A single eddy current separator.

Collection bins were placed under the eddy current separator in order to collect tailings samples and concentrate samples from material that was run. An Eriez 6" vibratory feeder was used along with an Eriez control unit that varied the output of the vibratory feeder by percent of output. A hopper found in the lab was modified so that it could feed the material to the vibratory feeder. The hopper and feeder were then mounted on the eddy current separator, and a chute was made to drop the material on a 6 inch by 6 inch area on the belt. There was a lip on the belt to remove ferrous particles that may get stuck in the rotor area, so this was the best option.

After the hopper and feeder were mounted on the eddy current separator, and the entire unit was enclosed in a structure built for dust containment. The dust containment structure is shown below in Figure 3.4, and did not interfere with the testing. The top of the hopper can be shown enclosed by the wooden box, pictured at top left of Figure 3.4. The Eriez control unit for the vibratory feeder is hanging from a stud with two orange wires connected to the bottom.

Fig. 3.4: Showing the enclosure for the eddy current separator.

The material itself was sized to -1 1/4 inch, and zorba metals were mixed with automotive shredder residue in order to produce a non-ferrous residue for testing. The size distribution of the material is fairly wide. Pictured in Figure 3.5 are the copper pieces that were found in the concentrate, at the right, and copper particles found in the tailings at the left. Because there was not bottom size all particles under 1.25 inches that came out of the shredder would be in this fraction.

Fig. 3.5: Copper found in the concentrate (right), and copper found in the tailings (left)

Other constituents of interest of the feed are aluminum, brass, circuit boards, and insulated copper wire (ICW) pictured in Figure 3.6. The feed also included fluff, which is a generic mixture of plastics, fabrics, dirt, wood, foam, and glass.

Fig. 3.6: Constituents of the feed tested including aluminum (top left), brass (top right), ICW (bottom right), and circuit board (bottom left).

Other apparatus used included a forklift with a barrel lifter attachment, shovels, and buckets.

3.3 PROCEDURE

First, zorba metals were mixed with automotive shredder residue (ASR) in order to create a residue containing nonferrous metals. The metals were mixed with the ASR so that the resultant residue contained about 10% aluminum and 2% red metals, which are brass, bronze, and bare copper, by weight. Batches of 200 lb were mixed at a time, which was about the capacity of the hopper and the large bin in place to collect fluff. All materials were weighed in a plastic drum, sealed, and tumbled five times using a barrel lifter.

Before this material was run, the settings for the eddy current separator needed to be chosen. These settings would stay constant for the entire test. Settings were chosen that were expected to produce a good separation. The settings were chosen, in this case, based on the operator's experience of these parameters effect the separation, in both real world testing and simulation software. The belt speed was chosen to be constant at 2.0 m/s. Belt speed changes the horizontal velocity and travel of all particles. It may be necessary to increase belt speed in order to recover finer aluminum and copper particles, which are not effected as much by the eddy current field, however a greater belt speed can produce a lower grade, concentrate. The setting of 2.0 m/s is somewhat fast, but not at the fastest setting of 2.5 m/s allowed by the control unit.

The splitter setting used is shown in Figure 3.7. The belt and rotor are just right of what is in the illustration. This setting was chosen after running some material at a low feed rate with this splitter setting. It appeared to create a mostly clean product. The federate was arbitrarily chosen to be 60% on the vibratory feeder control box. This was found to be a low federate, about 1.15 tons per hour per foot of belt width, and allowed the federate to be increased for locked cycle testing. Because of the chute design, the federate is a maximum value, the true federate is unknown and is slightly lower due to material spreading out on the belt.

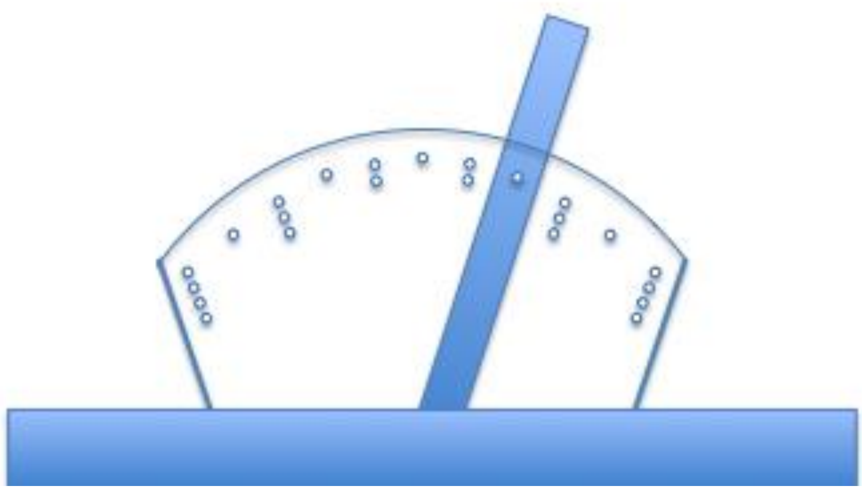


Fig. 3.7: Splitter setting used in testing.

For the first test 3 200lb barrels were run in order to collect about 70 lb of material of concentrate needed for assaying. A limitation for this experiment was the amount of material available for testing. Ideally one would want at least a 70 lb sample for every product of the tree analysis, but this was not possible due to the amount of material available for testing and time constraints. The products of the first separation were then split following a path similar to the one shown in Figure 3.1. For this tree analysis, a material was not run through the eddy current separator more than six times. By the sixth time the ASR was processed, only a small mass of metal was removed by the eddy current separator. The pure concentrate, and the pure tailings were processed six times, however if it was determined that a sample towards the middle of the tree was much too small of a sample size, or further processing may cause a substantial loss of material, the branch was stopped.

Samples were labeled according to the following convention:

- For material that originally reported to the zorba concentrate, the label started with a C.
- For material that originally reported to the fluff tailings, the label started with a T.
- After the second level of processing a C or T would be the second letter, or digit, depending on weather the material reported to the concentrate or tailings.
- After the nth level of processing a C or T would be the nth letter, or digit, depending on weather the material reported to the concentrate or tailings.
- The number of digits in the label indicates the number of times the material has been processed by the eddy current separator.

Some examples are shown in Table 3.1:

Label	Description
CCC,CCC	The material has been processed 6 times and reported to the concentrate every time.
TC,CTC	The material has been processed 5 times and has reported to the tailings, then the concentrate, the concentrate, the tailings and then the concentrate, in that order.
TTC	The material has been processed 3 times. The first and second runs it reported to the tailings. After the third level of processing it reported to the concentrate. The sample was not run further due to small sample size.

Table 3.1: Examples of Tree Analysis sample labeling.

Using this convention it is easy to determine, how many times the material has been processed, and its location on the tree.

Test 1 was conducted in order to obtain results from rougher, rougher-cleaner, and rougher-scavenger circuits. Tests 2, 3, and 4 employed rougher-cleaner-scavenger, rougher-cleaner, and rougher-scavenger tests with recirculating loads. The tree analysis from these tests were conducted in the same manner as Test 1, except the split indicated by "R" in Figure 3.1 was the result of a locked cycle test.

For Test 2 the locked cycle test mimicked a rougher-scavenger-cleaner circuit. In order to conduct the locked cycle test 200 lb batches of nonferrous residue were run, and samples were collected as shown in Figure 3.8. All settings on the eddy current separator were kept constant for all stages. The same settings for the eddy current separator were used for every stage of every test.

For the first run of the locked cycle test middlings, from the first level scavenger (MT) and the first level cleaner (MC), do not exist until the material is processed and can be ignored as part of the feed. After the first run the middling's produced from the nonferrous residue are combined and weighed. Then, another standard 200 lb of nonferrous residue were mixed, but the middling's were also added in. The locked cycle circuit shown in Figure 3.8 is completed again. The setting on the control box is adjusted in proportion to the increase in feed mass due to the added middlings. The concept behind changing the feed rate is, if the circuit had to output a constant amount of material per hour, but now also had to process middlings, the added middlings may reduce the performance of the circuit. This forces the feed rate of the circuit to become an independent variable instead of a dependent variable.

Both the T and C samples are discarded until the mass of the middlings does not change much for two or more runs. This means that the recirculating load is stable, and therefore the locked cycle test is mimicking the intended RCS circuit. Material is run through the locked cycle circuit until about 70 lb of concentrate is collected.

For Test 3, a locked cycle test that mimicked a rougher-cleaner circuit was used. Once again nonferrous residue was processed until the mass of the middlings stabilized, then samples were collected at this point. The locked cycle diagram for Test is depicted in Figure 3.9. Test 4 conducted in the same manner as Test 2 and Test 3, except a rougher-scavenger circuit was used. The locked cycle diagram for Test 4 is shown in Figure 3.10.

After enough sample was collected for all locked cycle tests, the products of the test were run through a tree analysis with the same procedure as Test 1.

All samples were assayed after collection. Due to the learning curve of assaying, some of the procedures changed from test to test, but the methods were kept constant for individual tests. Samples were assayed for aluminum, aluminum wire, bare copper, brass/bronze, circuit boards, insulated copper wire, and fluff. Figure 3.11 shows a tailings assay being conducted. Any ferrous or stainless steel particles found were included in the fluff. The material that went to tailings every time was coned and quartered in order to obtain a smaller, representative sample estimated to be 75 lb at the time of coning and quartering.

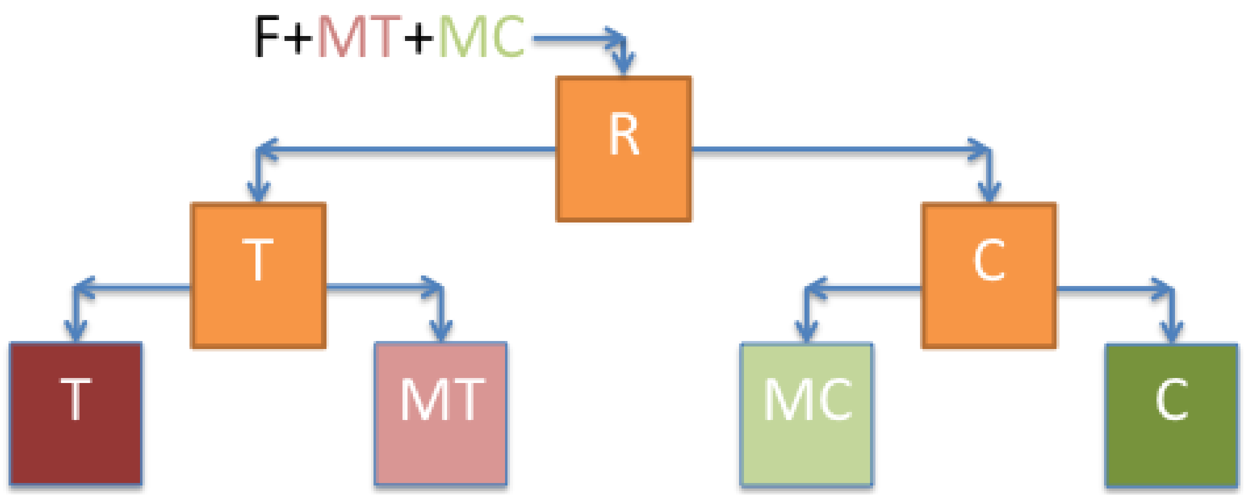


Fig. 3.8: Stages and samples collected for the locked cycle test used in Test 2.

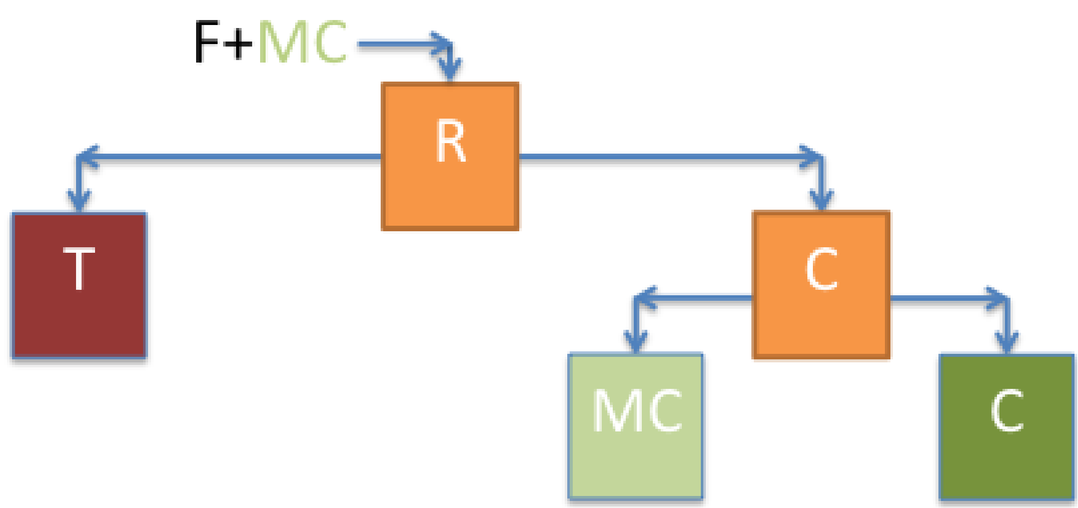


Fig. 3.9: Stages and samples collected for the locked cycle test used in Test 3.

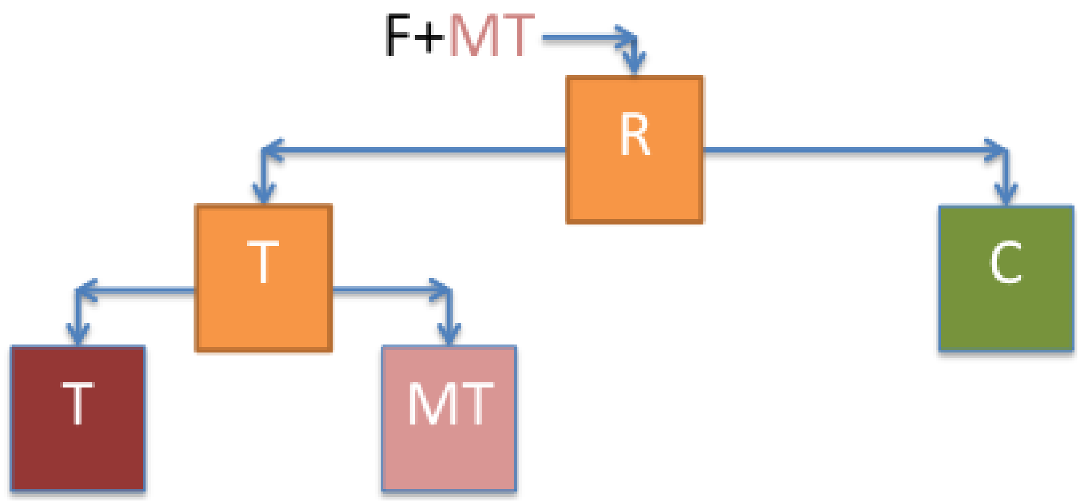


Fig. 3.10: Stages and samples collected for the locked cycle test used in Test 4.

Figure 3.11: Tailings sample assay procedure, most of the sample is fluff.

3.4 RESULTS AND DISCUSSION

3.4.1 CIRCUIT RESULTS

The results from specific circuits are shown in Table 3.2. From the tree analysis from Test 1, it was possible to calculate the results of more complex circuits that did not require a recirculating load.

Table 3.2: The results of individual circuits.

Test Number	Description	Zorba Grade	Zorba Recovery	Al Grade	Al Recovery	Red Metals Grade	Red Metals Recovery
Test 1	Rougher Only	94.05	86.09	77.80	97.37	16.25	55.37
Test 1	Rougher- Cleaner	98.07	84.58	81.30	95.87	16.77	53.85
Test 1	Rougher-Scavenger	93.42	87.97	75.87	97.69	17.55	61.51
Test 1	Rougher-Cleaner-Scavenger	97.29	86.46	79.15	96.19	18.13	59.99
Test 2	R-C-S Locked Cycle	98.94	91.37	86.83	96.91	12.11	64.83
Test 3	R-C Locked Cycle	98.73	88.24	85.79	94.01	12.94	62.73
Test 4	R-S Locked Cycle	95.00	86.17	83.40	94.16	11.60	53.52

These results do not show much variation from test to test. There are a few reasons for this, including the small recirculating load that was used in the locked cycle tests. Figure 3.12 shows the mass of the middlings, used as a recirculating load, as a percent of the new feed added to the locked cycle test. The middlings weights for Test 2 were not recorded for each run, however the mass eventually stabilized at about 1% of the feed or 2 lb. This small mass makes the recirculating streams have a minimal impact on the performance, compared to the large impact shown in the Eriez RCS system.

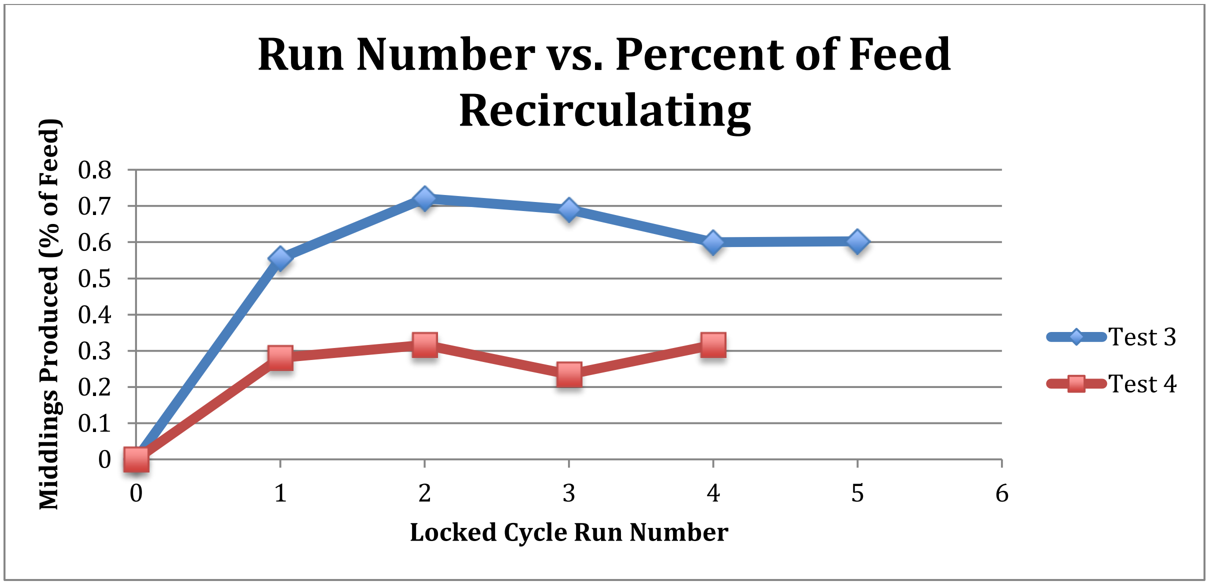


Fig. 3.12: The recirculating load in locked cycle testing as a percentage of the feed.

Another possibility that could explain unexpected variations in the data is that the feed changed over time. The material was run many times, and eventually some of the particles can break down, effectively changing the size distribution.

The performance of locked cycle tests can also change the size distribution in the feed, which would have an impact on the next test. It is very likely that this had an effect on Test 4. Table 3.2 shows that the zorba recovery for Test 4, which used a rougher scavenger, is less than in Test 3, which used a rougher cleaner. This is opposite than what would be expected. Before Test 4 was run, another test was run that had a recirculating load upwards of 28% of the feed. This was achieved by using a splitter position that was much closer to the belt than all other tests. A particle's size has a large impact on the distance it is thrown by an eddy current separator (Zhang et. al. 1998). Moving the splitter in, allowed more fine particles to be recovered and concentrated in the middlings, which were mixed in with new feed. This could have changed the size distribution of metals in the feed. When the splitter was moved back out for Test 4 these particles had a much lower probability of ending up in the concentrate, but still counted as a loss when conducting an assay.

3.4.2 TREE ANALYSIS RESULTS

3.4.2.1 OVERVIEW

This section covers the results obtained through tree analysis. In order to generate the operating boundary samples were first ordered from the highest to the lowest grade. The definition of grade may change between plots depending on the material of interest, for example copper grade is different than zorba grade. Then the mass distribution of all of the constituents was calculated. From there cumulative grade, recovery, and rejection could be calculated for each sample in the order of the descending grade. All data, calculated numbers, tree diagrams, and larger versions of the plots can be viewed in Appendices 2, 3, 4, and 5.

3.4.2.2 ZORBA GRADE AND RECOVERY

Using the assayed samples from Tree analysis, it was possible to generate Grade vs. Recovery boundaries. The plots in Figures 3.13 to 3.16 show grade vs. recovery boundaries for all tests in regards to zorba. The circuits indicated by distinct points on the plots represent the data in Table 3.2.

In Figure 3.13 all of the circuits that could be derived from Test 1 are shown. The rougher scavenger has a slightly higher recovery than the rougher, but a worse grade. The rougher cleaner is operating in a different direction with a slightly lower recovery, but a higher grade. These are both as expected. The rougher-cleaner-scavenger circuit is operating with both a higher grade and a higher recovery, but neither value is quite as high as the highest value achievable with a two unit circuit. The rougher-cleaner-scavenger circuit would theoretically be expected to produce the same results as just the rougher.

It is clear that none of the points in Figure 3.13 are operating at the boundary. This means that with the same feed and machine settings used, there could potentially be an improvement in efficiency if different circuits were used.

Figure 3.14 shows the results of the rougher-cleaner-scavenger locked cycle test and tree analysis. This point is operating very close to the elbow of the boundary generated from tree analysis. It is not right on the elbow, but it is still closer than any of the points in Figure 3.13.

Figure 3.15 shows the results of the rougher-cleaner locked cycle test and tree analysis. It appears that the point showing the results of the first separation is lower in relation to the boundary on the y-axis. This illustrates a lower recovery than what is optimal at that grade. The difference in grade from the point to the boundary appears to be about the same as it is in Test 2.

In Figure 3.16 the results from the rougher-scavenger locked cycle test are plotted. The grade for the locked cycle test has been pushed further away from the boundary, but the distance from the point to the boundary on the y-axis appears to be less than it was for the rougher-cleaner locked cycle test.

The boundary point, shown on the plots in Figures 3.13-3.16, that has the highest recovery and the lowest grade, should be noted. The sample was used to create that point had a lower zorba grade than any other sample, besides the material that always went to the tailings. During tree analysis the material that ended up in the pure tailings sample TTT,TTT went under the splitter as a reject 6 or 7 times. All of the material that ends up in this sample could potentially be deemed unrecoverable. In a scrap yard an eddy current circuit with legs that were 5 or 6 units long may be not feasible economically. Knowing this, the leftmost point shown on the grade/recovery boundary is the maximum recovery possible with the machine settings and feed used in that test if the metals that ended up in TTT,TTT are considered unrecoverable.

It should be noted that Test 4 had the lowest possible recovery, while Test 2 had the highest possible recovery on the boundaries.

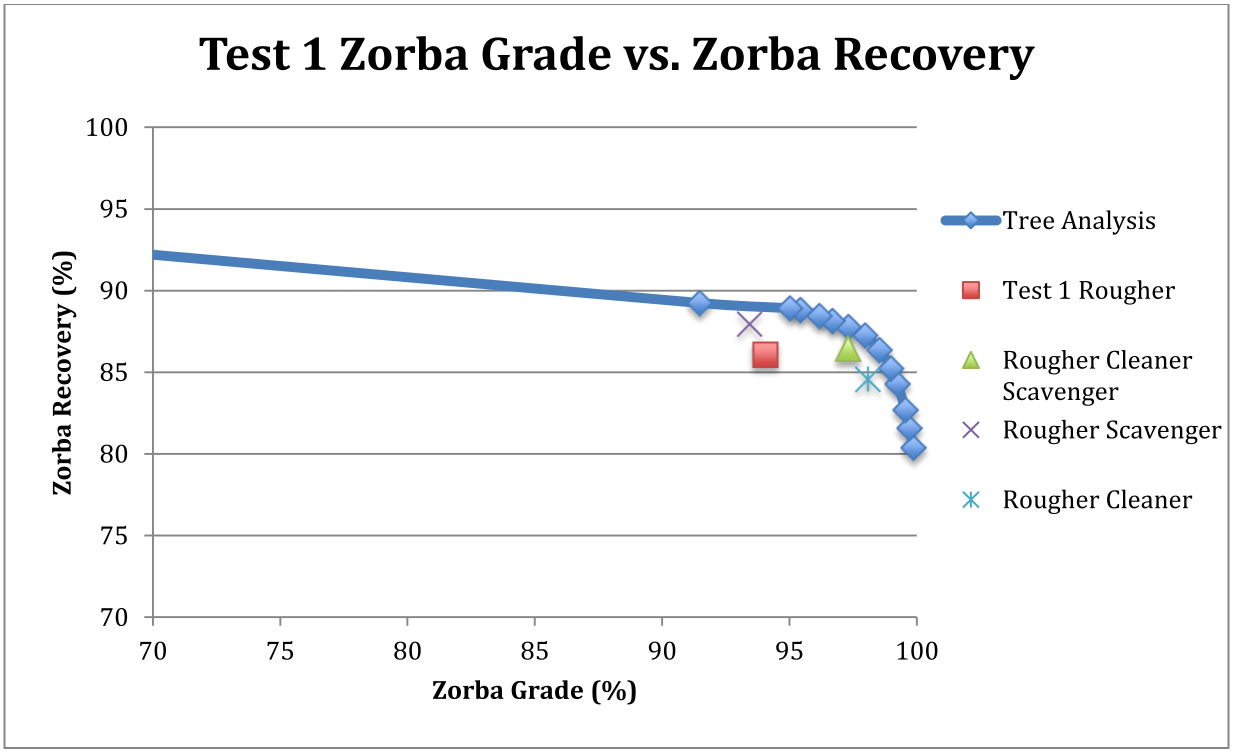


Fig. 3.13: Test 1 zorba grade vs. zorba recovery.

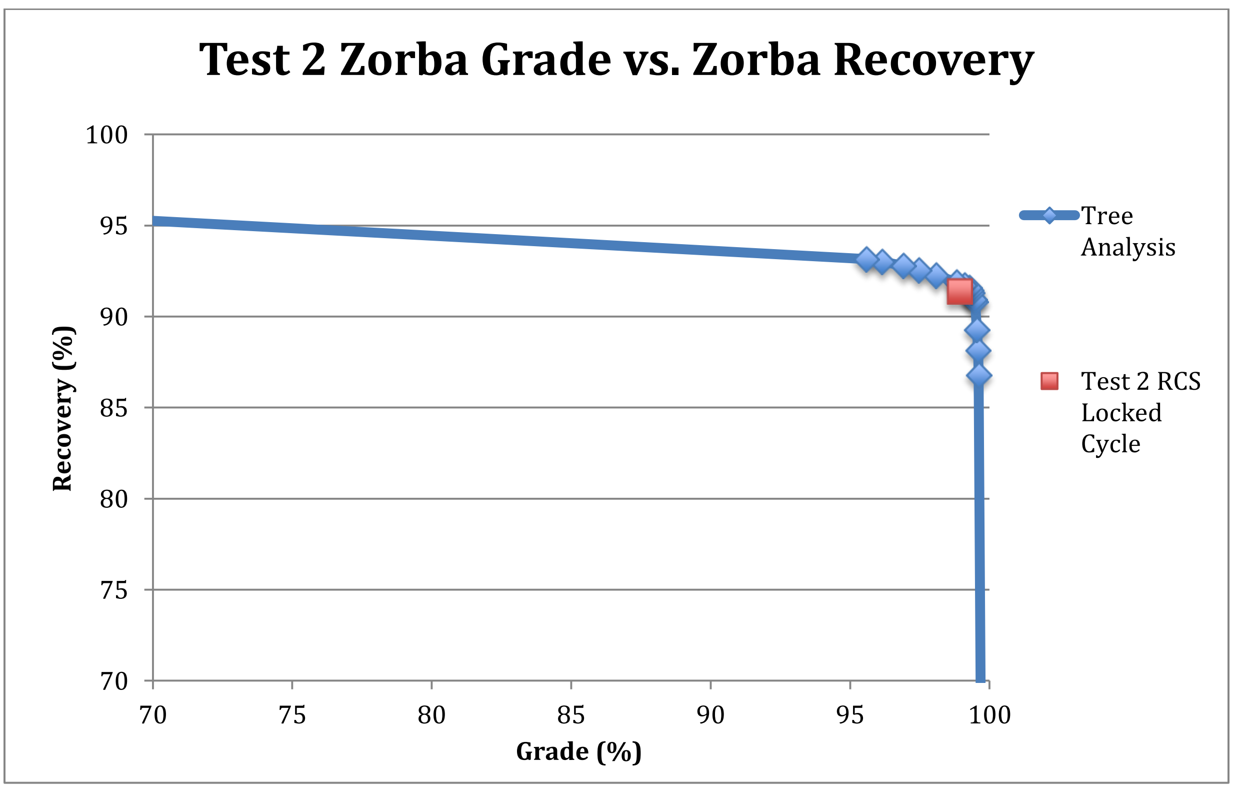


Fig. 3.14: Test 2 zorba grade vs. zorba recovery

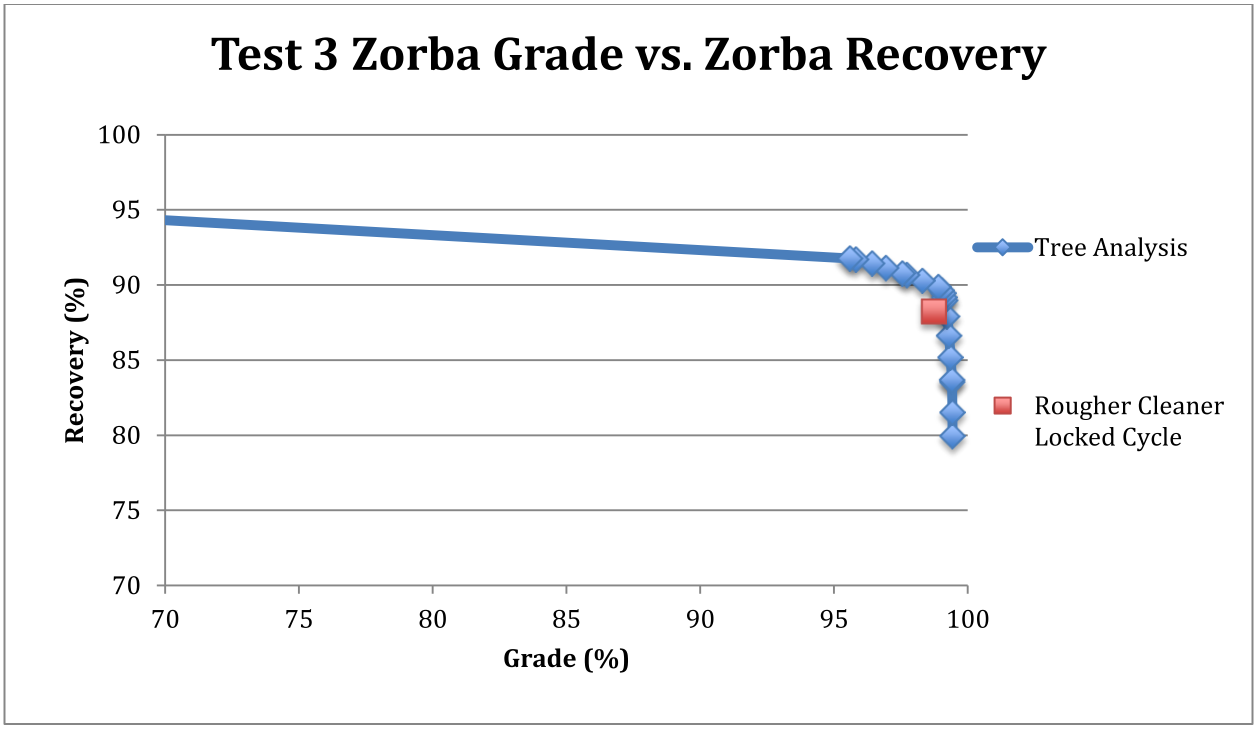


Fig. 3.15: Test 3 zorba grade vs. zorba recovery.

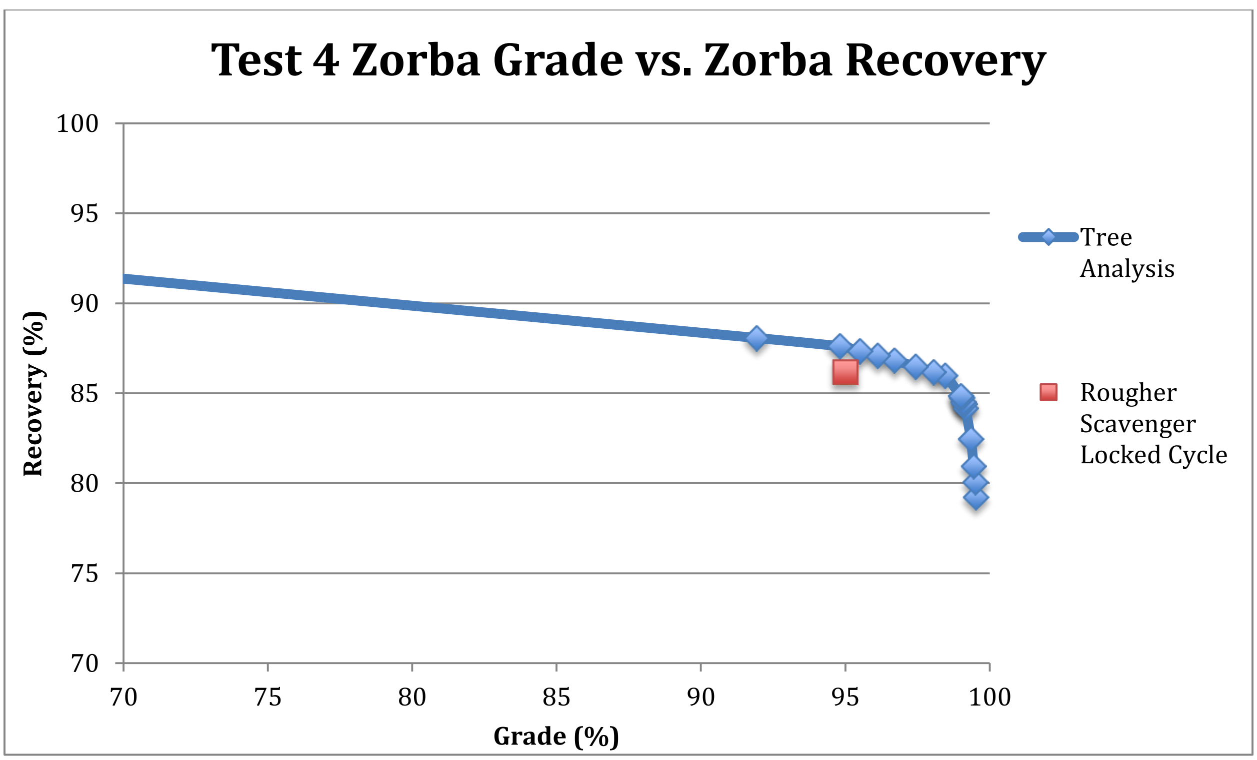


Fig. 3.16: Test 4 zorba grade vs. zorba recovery.

3.4.2.3 ALUMINUM GRADE AND RECOVERY

Grade/recovery boundaries were generated in the same manner as in section 3.4.2.2, except aluminum grade was used instead of zorba grade. All data, calculated numbers, and larger plots can be seen in Appendicies 3-6.

For Test 1, shown in Figure 3.17, both the rougher scavenger and the rougher had fairly high recoveries of aluminum. Although the rougher cleaner scavenger outperformed the rougher overall on zorba, the rougher has a higher recovery of aluminum than the rougher cleaner scavenger. The rougher cleaner has the highest grade.

In Test 2, shown in Figure 3.18, the RCS locked cycle test once again performed very close to the elbow of the boundary. The RCS point in Test 2 may be able to improve slightly in regards to grade.

Test 3, shown in Figure 3.19, shows the rougher cleaner locked cycle test. It is operating very close to the most efficient point on the curve.

Test 4, shown in Figure 3.20, shows the rougher scavenger locked cycle test. It appears this point is close to the optimal aluminum recovery, but it could improve in grade.

It should be noted that the maximum grade for each plot is between 80% and 90%. This is because any zorba material, such as bare copper wire, is considered a contaminant, but still has a higher probability it will end up in the concentrate than fluff. Using these machine settings, it would be impossible to obtain a perfect separation between red metals and aluminum, no matter how many machines were used.

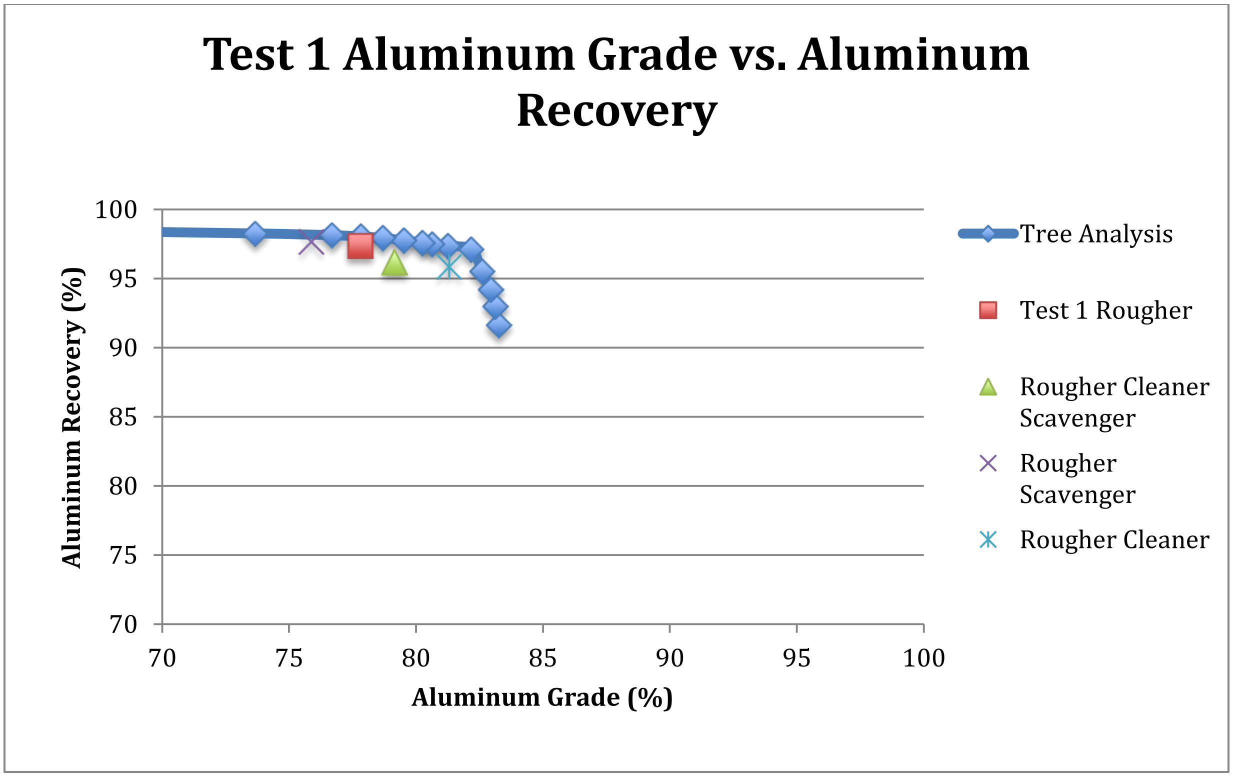


Fig. 3.17: Test 1 aluminum grade vs. aluminum recovery.

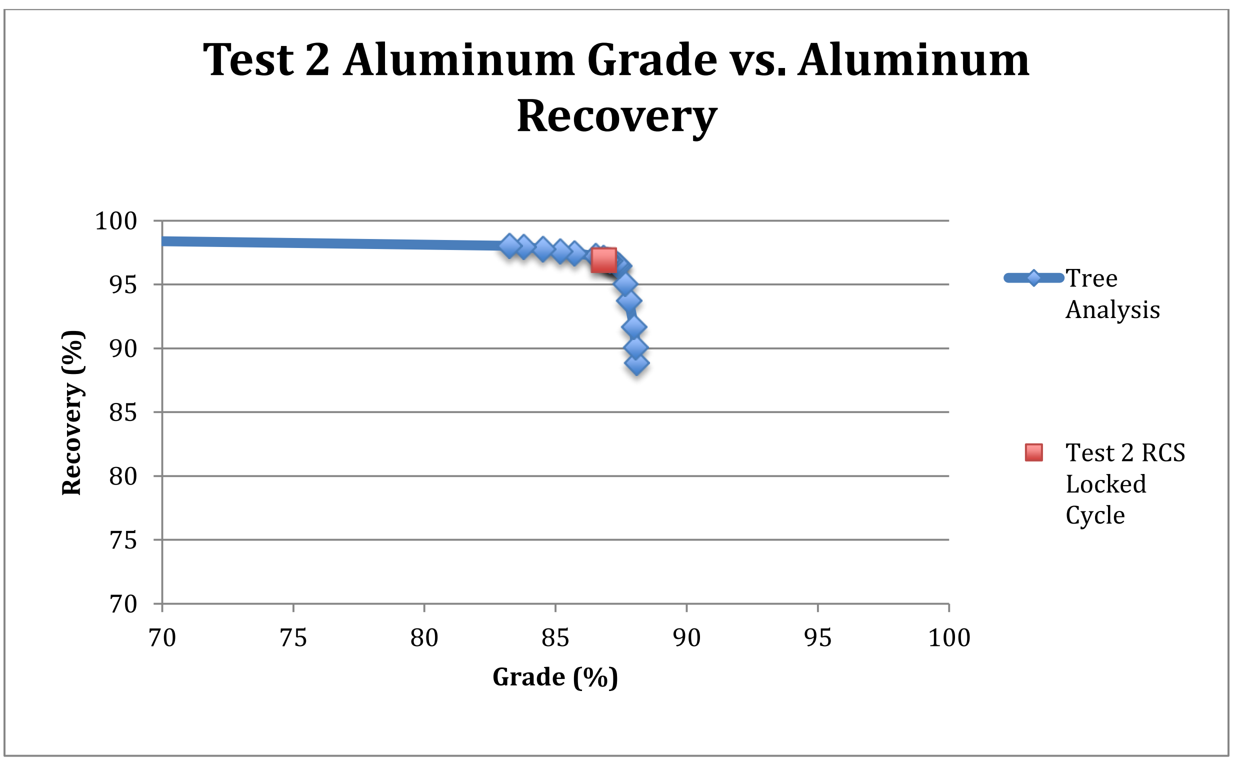


Fig. 3.18: Test 2 aluminum grade vs. aluminum recovery.

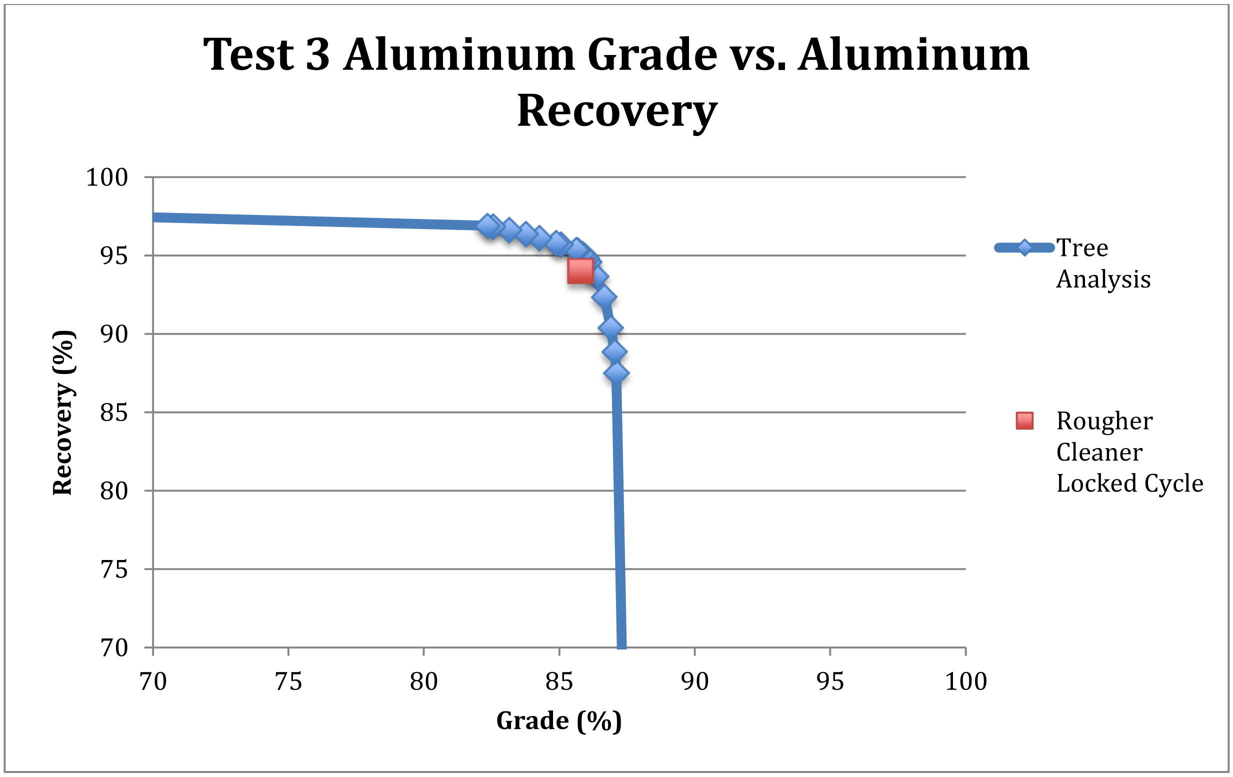


Fig. 3.19: Test 3 aluminum grade vs. aluminum recovery

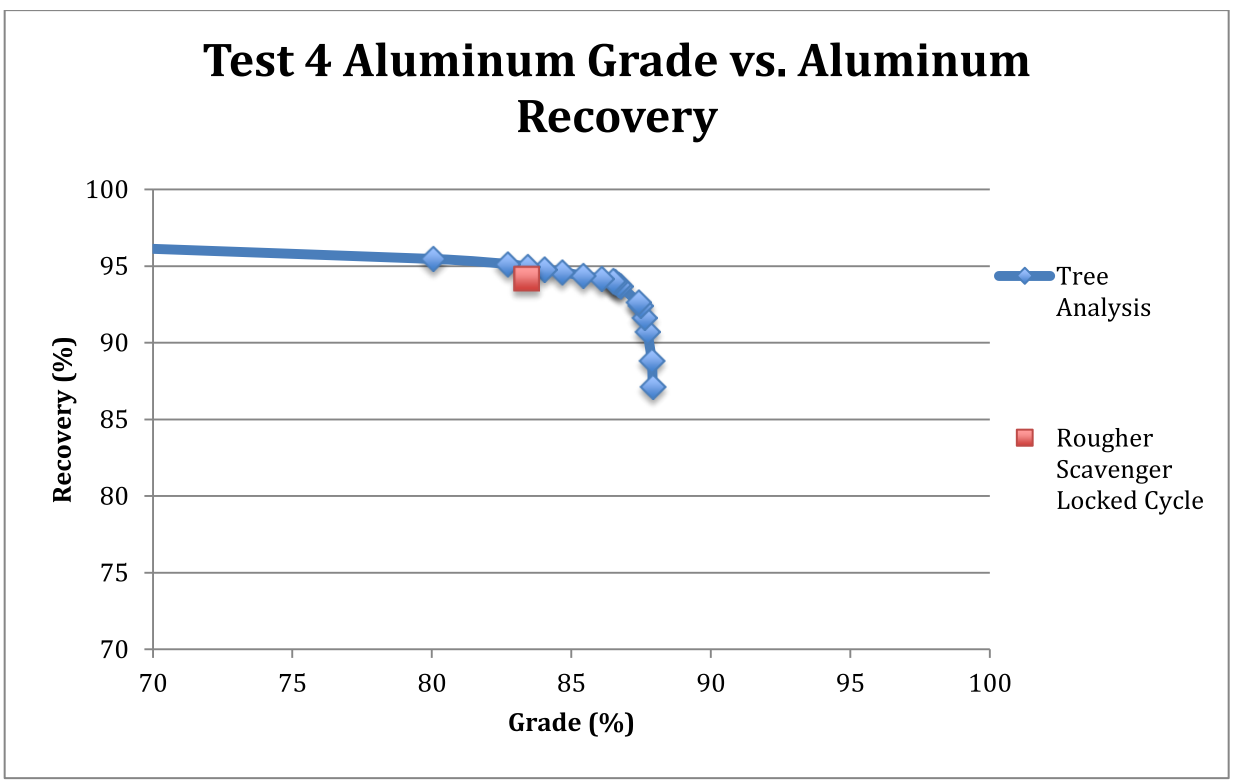


Fig. 3.20: Test 4 aluminum grade vs. aluminum recovery.

3.4.2.4.1 GRADE AND RECOVERY

For all tests red metals grade vs. red metals recovery plots were generated along with the associated grade/recovery boundary. As shown in Figures 3.21-3.24, these boundaries are in an unconventional shape. The same methods were used to generate these plots that were used to generate zorba grade vs. recovery plots and aluminum grade vs. recovery plots.

When these plots were generated, aluminum was considered a contaminant for the calculation of red metals grade. This gives them the unconventional shape. These plots show that the maximum possible grade of red metals for a circuit with these settings on each machine is between 35% and 65%.

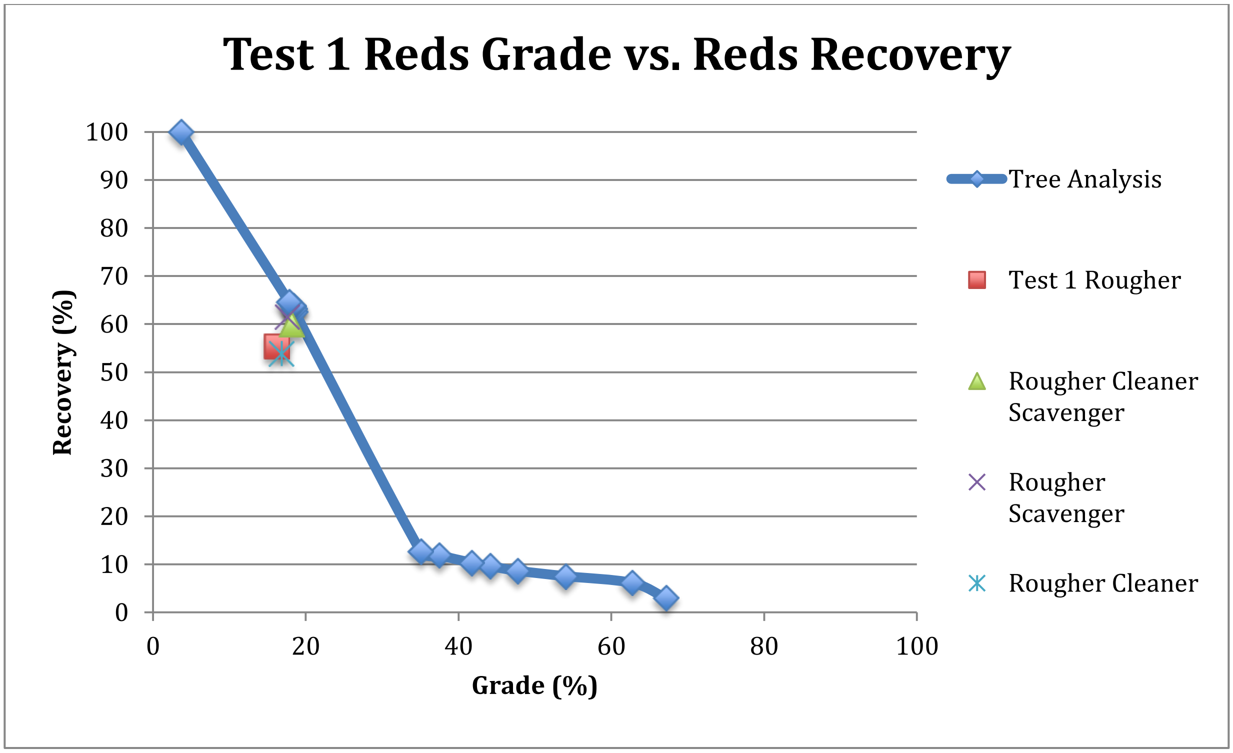


Fig. 3.21: Test 1 reds grade vs. reds recovery.

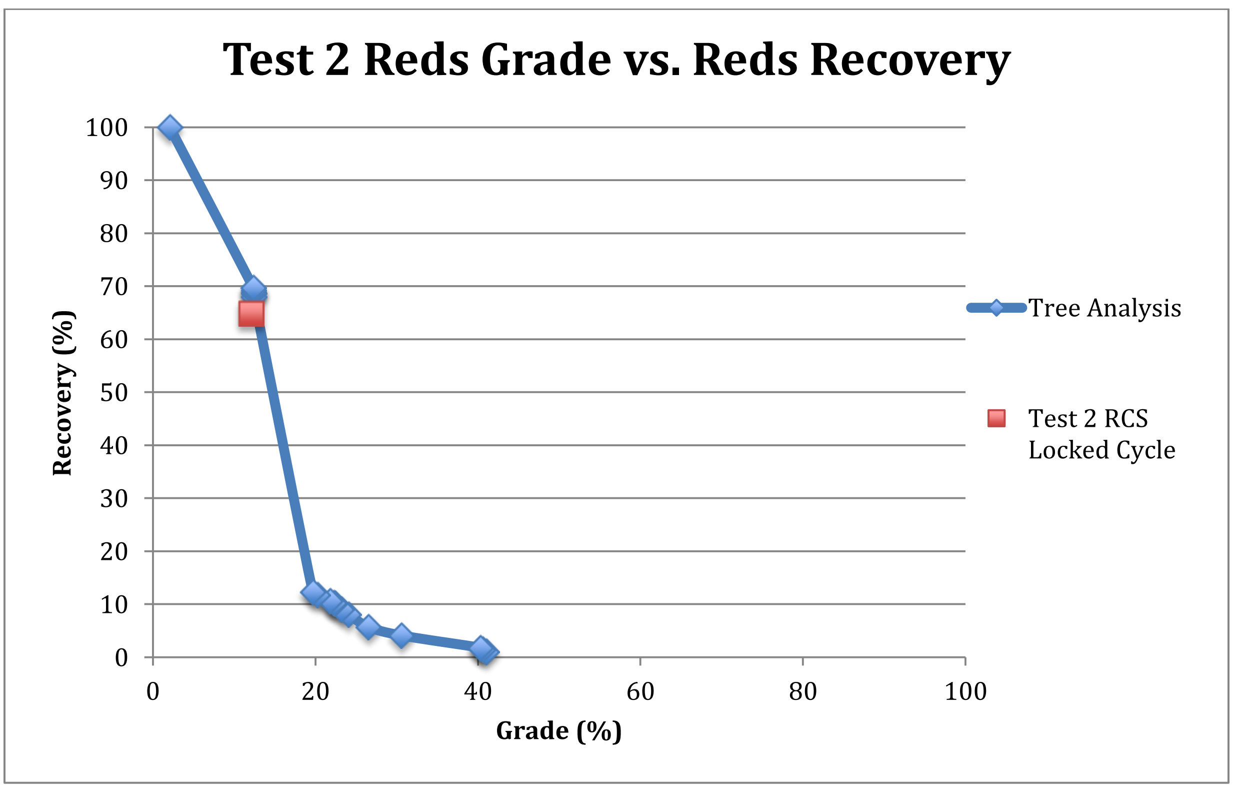


Fig. 3.22: Test 2 reds grade vs. reds recovery.

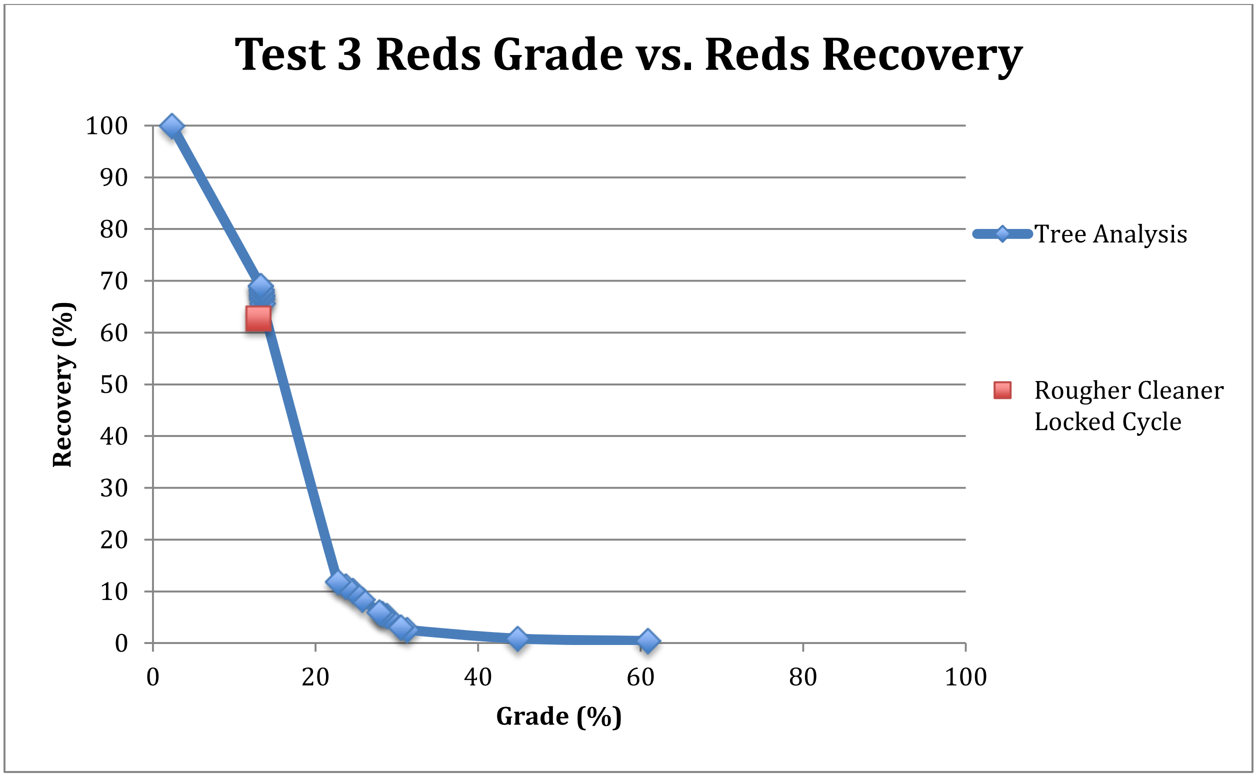


Fig. 3.23: Test 3 reds grade vs. reds recovery.

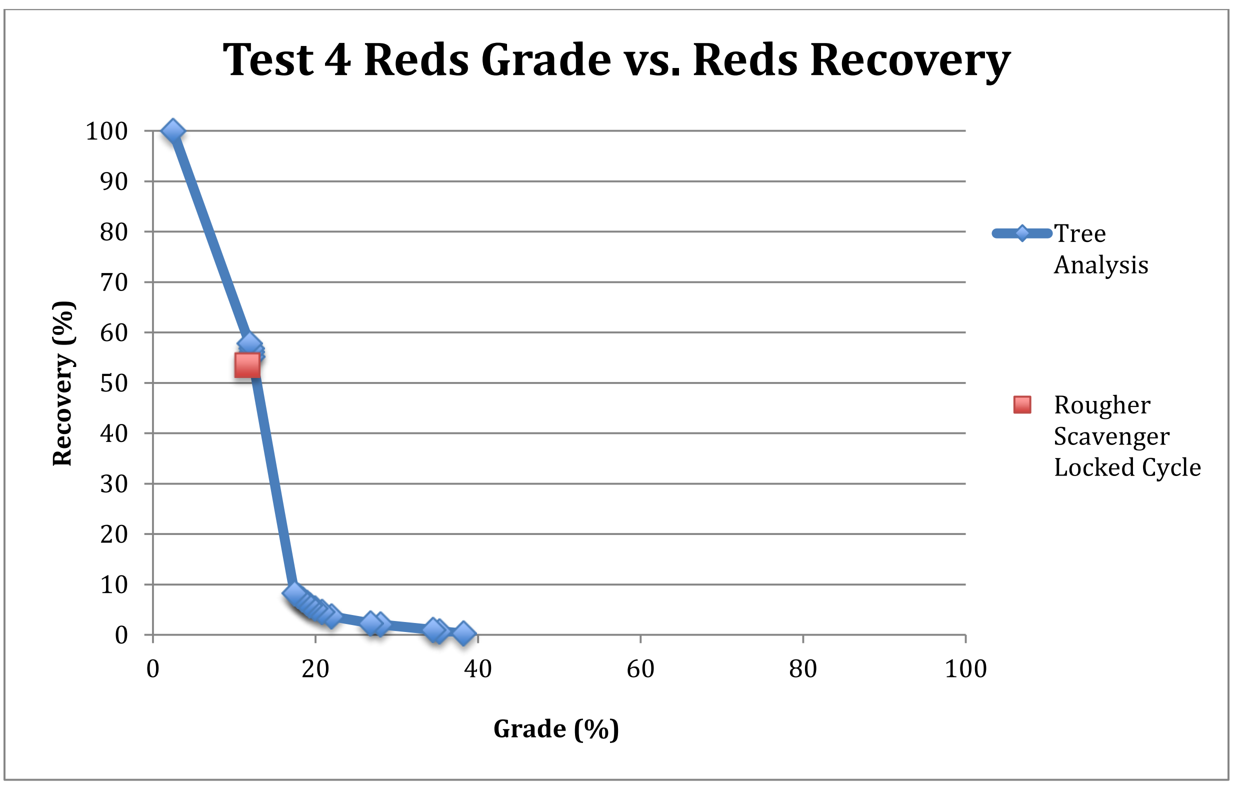


Fig. 3.24: Test 4 reds grade vs. reds recovery.

3.4.2.4.2 SPECIFIC REDS GRADE AND RECOVERY

The boundary for red metals grade vs. red metals recovery is unconventional. A calculation called specific grade was generated in order to better describe this process. The calculated values for the overall separations in each test are shown in Table 3.3.

Table 3.3: Data for circuits plotted on the specific grade vs. recovery boundaries.

Test Number	Description	Specific Reds Grade	Red Metals Recovery
Test 1	Rougher Only	73.18	55.37
Test 1	Rougher- Cleaner	89.68	53.85
Test 1	Rougher-Scavenger	72.72	61.51
Test 1	Rougher-Cleaner-Scavenger	86.98	59.99
Test 2	R-C-S Locked Cycle	91.94	64.83
Test 3	R-C Locked Cycle	91.06	62.73
Test 4	R-S Locked Cycle	69.90	53.52

Specific grade is a term, which was created to analyze this data in a way that made visual comparisons of plots easier. Specific grade only takes into account the specified material and the waste material. In this case aluminum does not fall into either of those categories and aluminum content does not change the specific grade of a sample. Specific grade is calculated as shown in Figure 3.25.

$$grade_x = \frac{mass\ of\ material\ x}{mass\ of\ x + mass\ of\ waste}$$

$$grade_{reds} = \frac{mass\ of\ red\ metals}{mass\ of\ red\ metals + mass\ of\ fluff}$$

Fig. 3.25: Showing a general calculation and the calculation used for specific grade.

Specific grade allows the grade to be more indicative of the ratio of the material of interest to the material not expected to be separated by an eddy current separator.

Test 1 (Figure 3.26) shows that the rougher cleaner scavenger did pretty well on the separation of red metals. The point is close to the boundary, and has a slightly lower grade than the rougher cleaner, and a slightly lower recovery than the rougher scavenger. The rougher scavenger recovered more red metals than the rougher at a slightly lower grade, while the rougher cleaner had a much higher specific grade of red metals for a small red metal loss. According to this boundary, the maximum red metal recovery is 64.7% At this point it seems that the grade recovery boundary is dependent on machine settings and feed content. Points are shifted within the boundary by using different circuits.

Test 2 (Figure 3.27) shows that the red metals recovery is close to the boundary at that specific grade. A higher specific grade does not necessarily mean a higher red metals to aluminum ratio, however If another scavenger was added to the circuit it should increase the red metals recovery. Aluminum recovery was almost on the boundary for Test 2, therefore not much more aluminum could be recovered. For that reason an increase in red metals recovery should mean an increase in the ratio of red metals to aluminum. For Test 2, the maximum red metals recovery is 69.8%.

For Test 3 (Figure 3.28) the rougher cleaner locked cycle test had a slightly larger gap between the boundary and the point on the y-axis than there was in Test 2. For this test the maximum red metals recovery achievable is 69%.

In Test 4 (Figure 3.29) there is a dramatic drop in specific reds grade, both in absolute value and relative to the specific grade/recovery boundary. This makes sense due to the nature of the scavenger circuit to create a product with a lower grade. The maximum potential recovery according to the tree analysis is 57.9%. This is much lower than what was possible in other tests. This may be due to the possibility of the change in the size distribution of the feed, or the material breaking down over time.

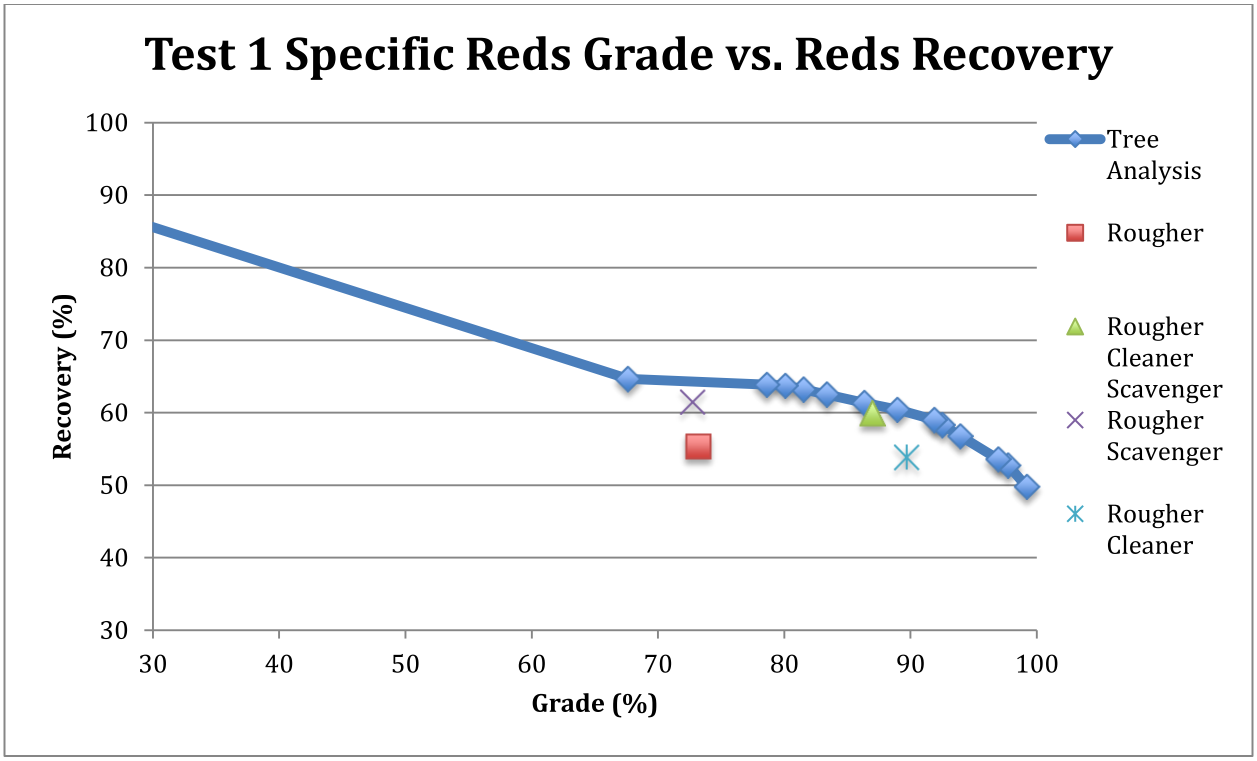


Fig. 3.26: Test 1 specific reds grade vs. reds recovery.

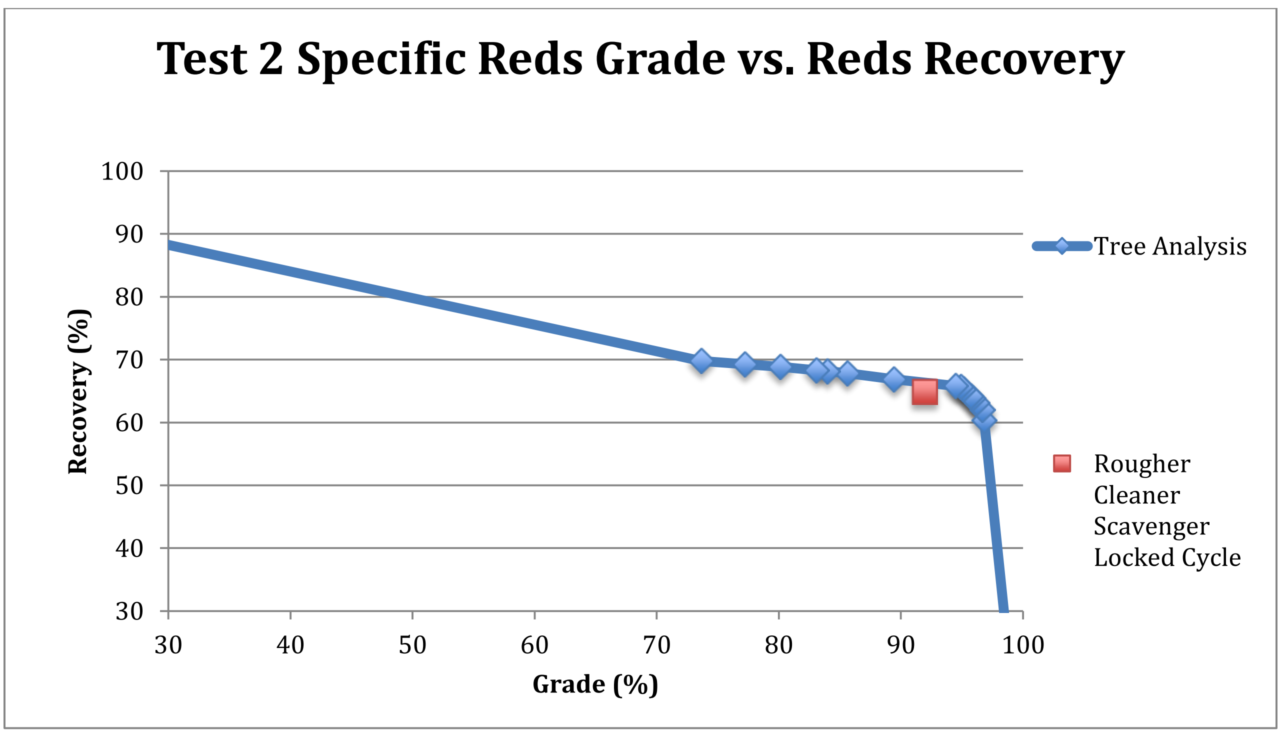


Fig. 3.27: Test 2 specific reds grade vs. reds recovery.

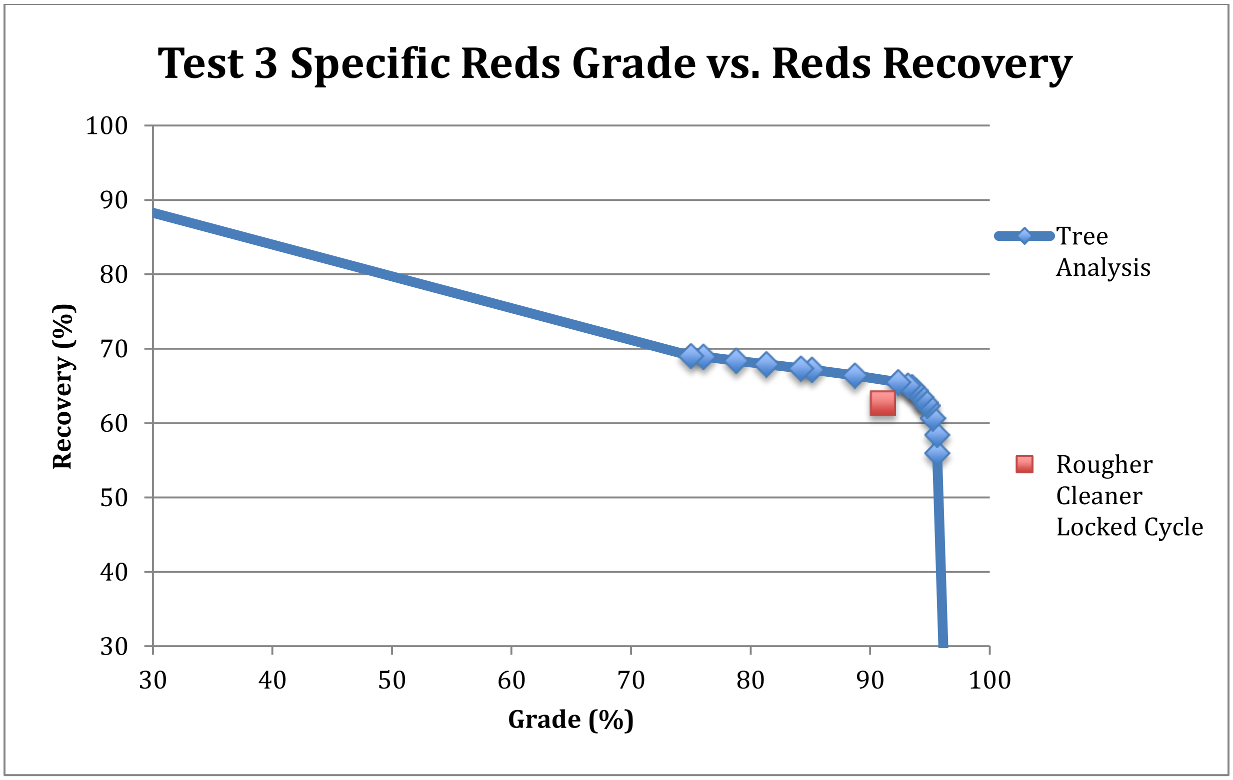


Fig. 3.28: Test 3 specific reds grade vs. reds recovery.

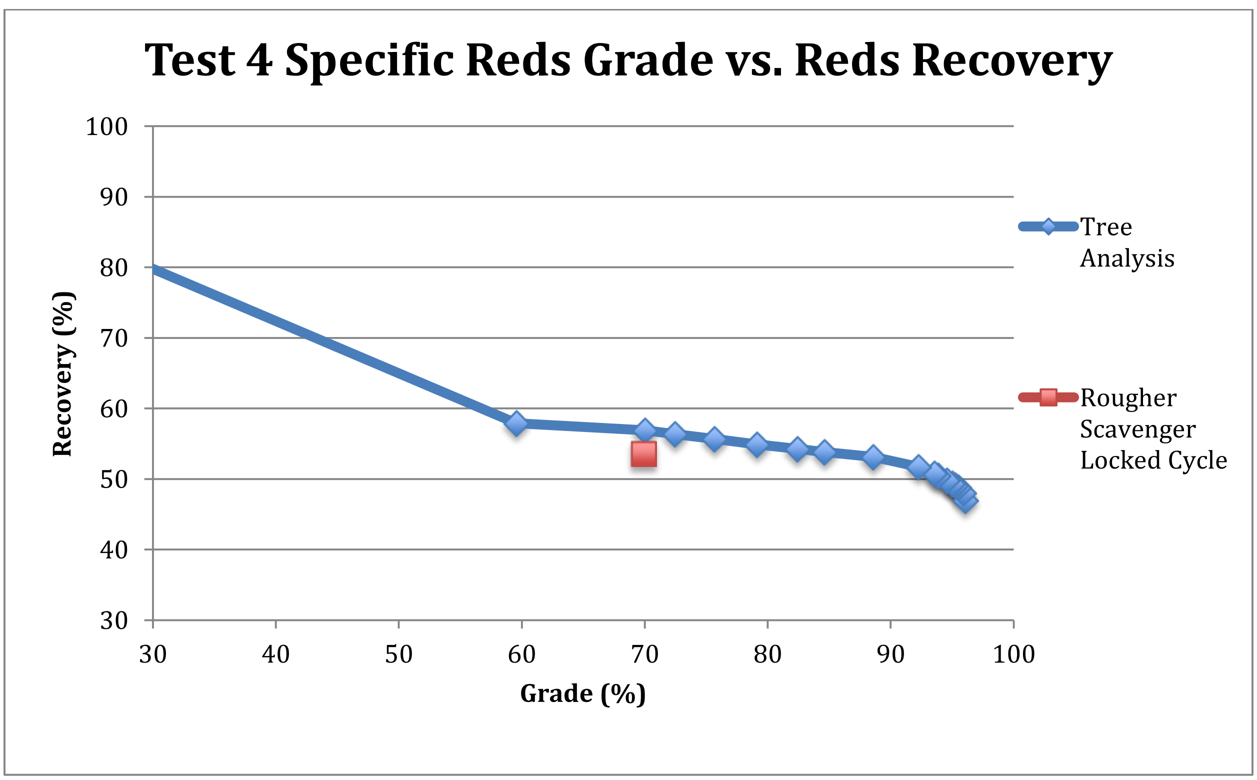


Fig. 3.29: Test 4 specific reds grade vs. reds recovery.

3.4.2.5 SEPARATION EFFICIENCY

In order to account for changes in feed, Zorba Recovery vs. Fluff Rejection plots were created from the data obtained through tree analysis. The data for the individual points is shown in Table 3.4. Theoretical efficency is a term used to describe the separation efficency of a circuit as a percent of the maximum separation efficency shown on the fluff rejection/zorba recovery boundary. Figures 3.30-3.36 show the rejection/recovery boundary for each circuit. Each of these plots has lines that indicate separation efficencies including the separation efficency of the circuit, and the maximum separation efficency on the boundary.

Table 3.4: Showing data for individual circuits associated with the rejection/recovery plots.

Test Number	Description	Fluff Rejection	Zorba Recovery	Separation Efficiency	Theoretical Efficiency
Test 1	Rougher Only	99.14	86.09	85.22	96.93
Test 1	Rougher- Cleaner	99.74	84.58	84.32	95.90
Test 1	Rougher-Scavenger	99.02	87.97	86.99	98.93
Test 1	Rougher-Cleaner-Scavenger	99.62	86.46	86.08	97.90
Test 2	R-C-S Locked Cycle	99.87	91.37	91.24	98.56
Test 3	R-C Locked Cycle	99.83	88.24	88.08	96.63
Test 4	R-S Locked Cycle	99.35	86.17	85.52	98.34

For Test 1 the maximum separation efficency on the rejection/recovery boundary is about 88.2%. The rougher, shown in Figure 3.30 had a separation efficency fo 85.22, which was 96.93% of the maximum separation efficency on the boundary. This is a higher separation efficency than the rougher cleaner, shown in Figure 3.31, which had a separation efficency of 84.32. Because the grades of all of the circuits are fairly high, the fluff rejection is also high. This makes makes the changes in recovery between circuits have a larger impact on the separation efficency. This is shown in the rougher-scavenger, in Figure 3.32 which has the highest recovery and separation efficency at 87.97 and 86.99 respectively. The rougher-scavenger also has the highest theoretical efficency at 98.93. The rougher-scavenger-cleaner, shown in Figure 3.33, had a theoretical efficency of 95.9%, one percent less than the rougher-scavenger, and had the third highest separation efficency in Test 1 at 86.08.

The RCS locked cycle test in Test 2, shown in Figure 3.34, has the highest separation efficency of any of the tests. The RCS locked cycle test also has the second highest theoretical efficency at 98.56. There were some slight assaying differences between Test 1 and 2, due to the learning curve of assaying the material by hand, and this in part could have caused this test to not have the highest theoretical efficency.

Test 3, shown in Figure 3.35, the rougher-cleaner locked cycle test, had the lowest theoretical efficency out of any of the locked cycle tests. This makes sense due to the high fluff rejection for all tests.

For Test 4, shown in Figure 3.36, the separation efficency of the rougher-scavenger test is the lowest out of all of the locked cycle tests, but the theoretical efficency is the second highest of the locked cycle tests at 98.34%.

Using rejection, recovery, separation efficency, and theoretical efficency can be a better indicator of which circuits have the best performance, than grade and recovery alone. The potential differences in feed and assay accuracy could be minimized, and it may make more sense to compare a test point to the boundary curve instead of an absolute value on the plot.

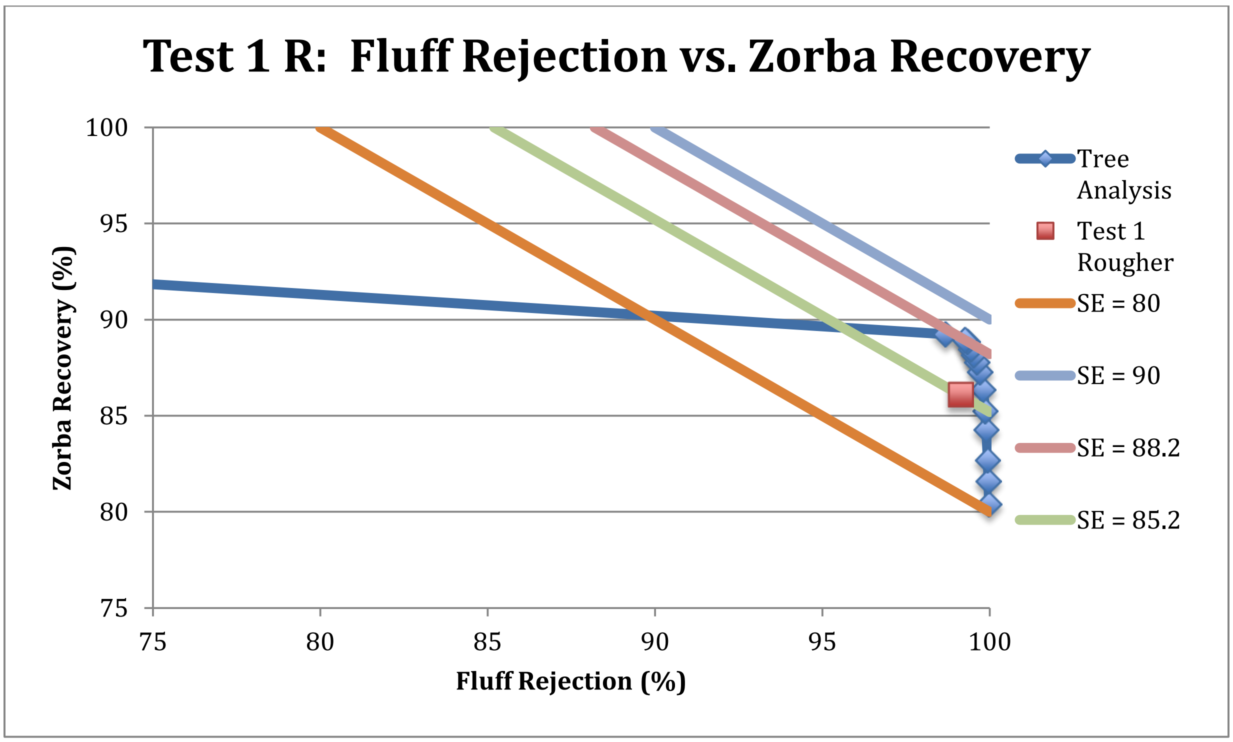


Fig. 3.30: Test 1 fluff rejection vs. zorba recovery, rougher only.

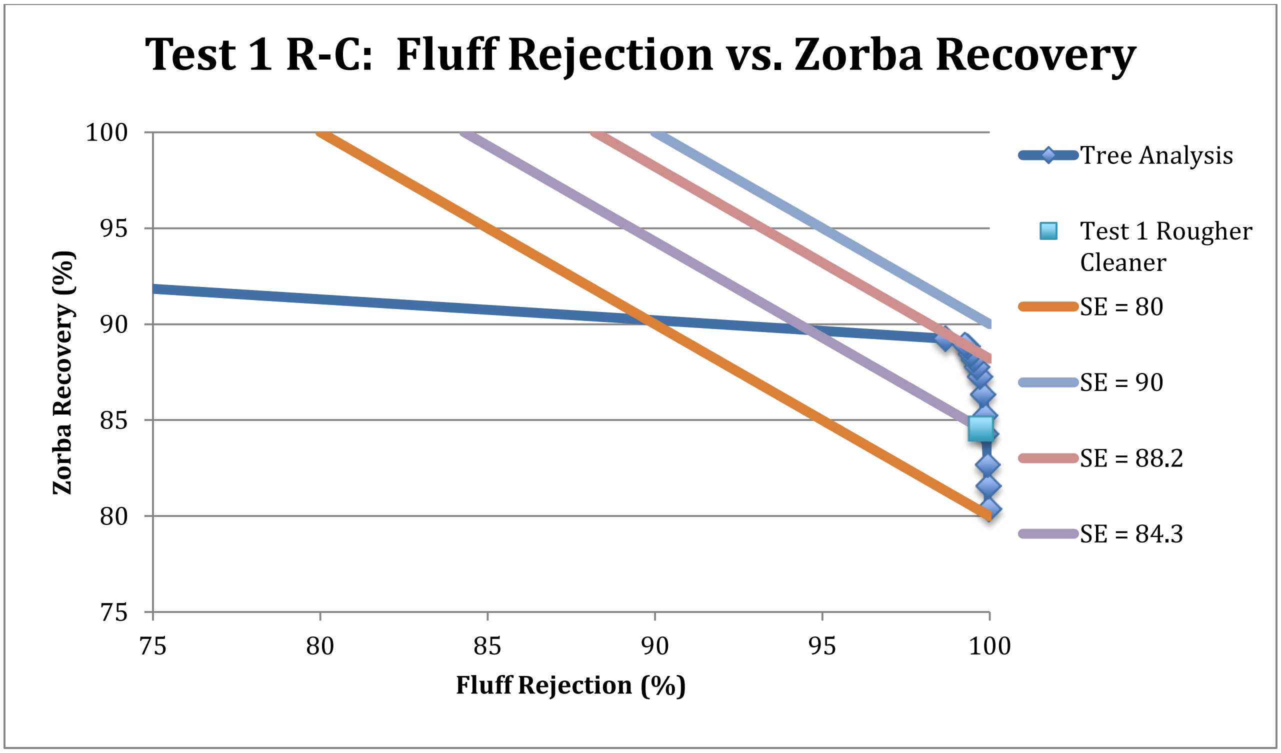


Fig. 3.31: Test 1 fluff rejection vs. zorba recovery, rougher-cleaner.

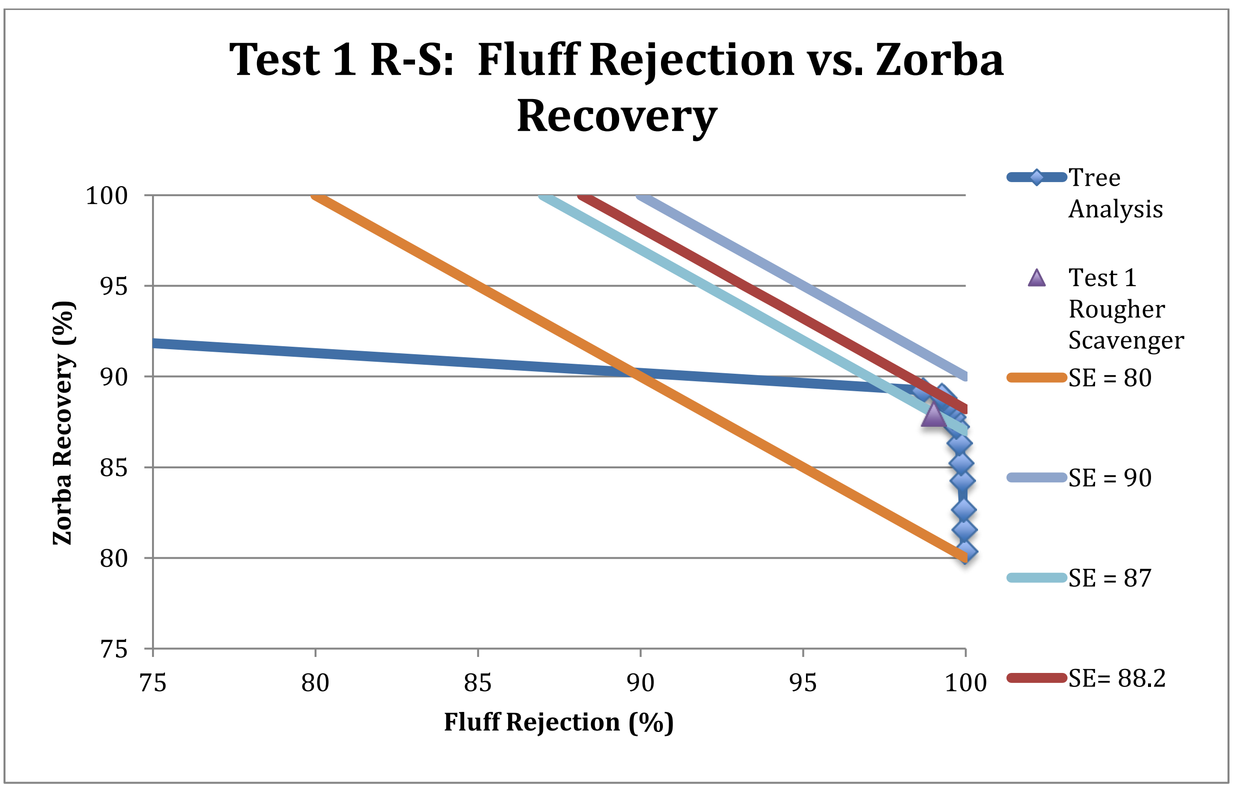


Fig. 3.32: Test 1 fluff rejection vs. zorba recovery, rougher-scavenger.

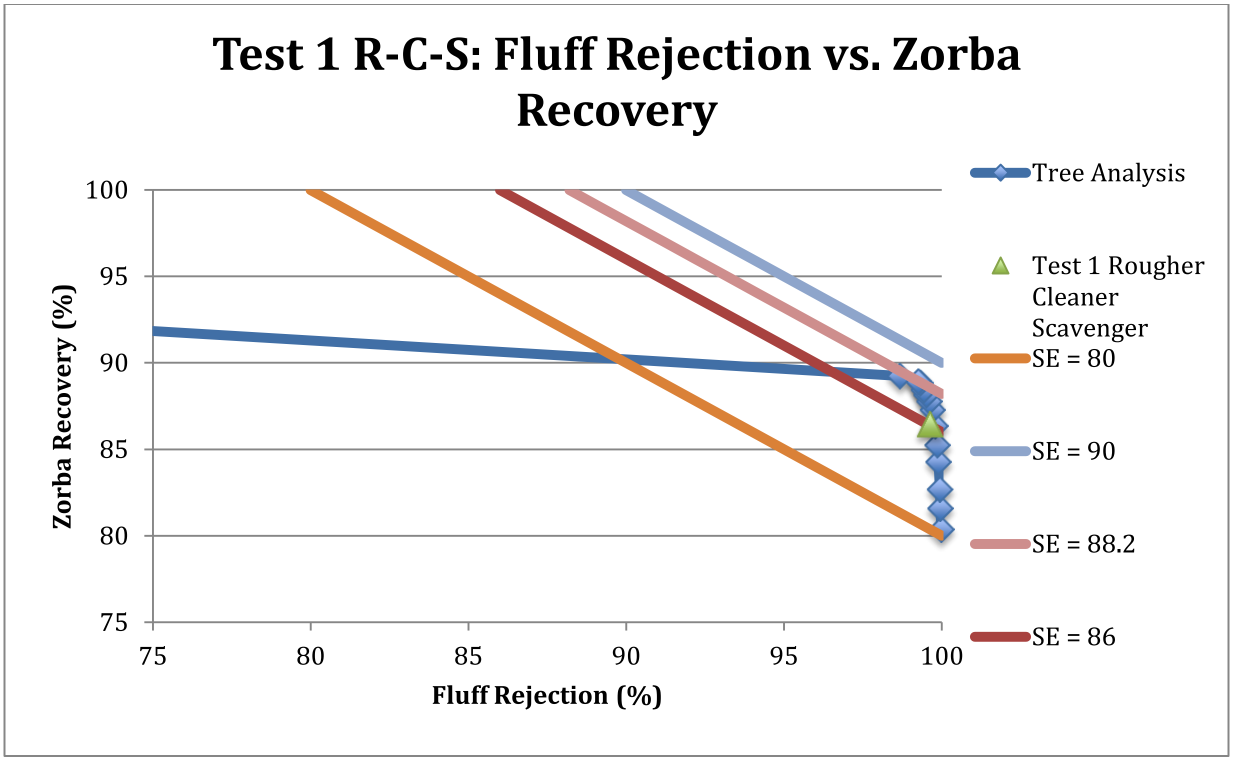


Fig. 3.33: Test 1 fluff rejection vs. zorba recovery, rougher-cleaner-scavenger.

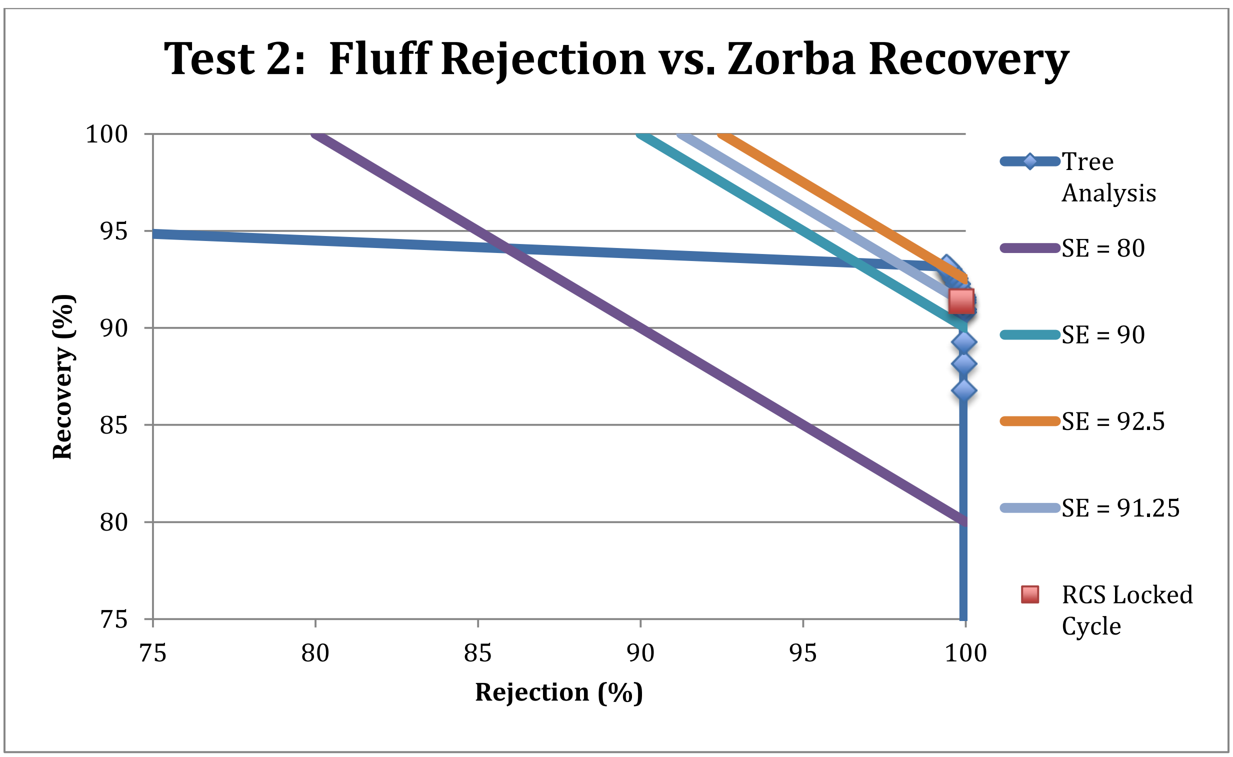


Fig. 3.34: Test 2 fluff rejection vs. zorba recovery, rcs locked cycle.

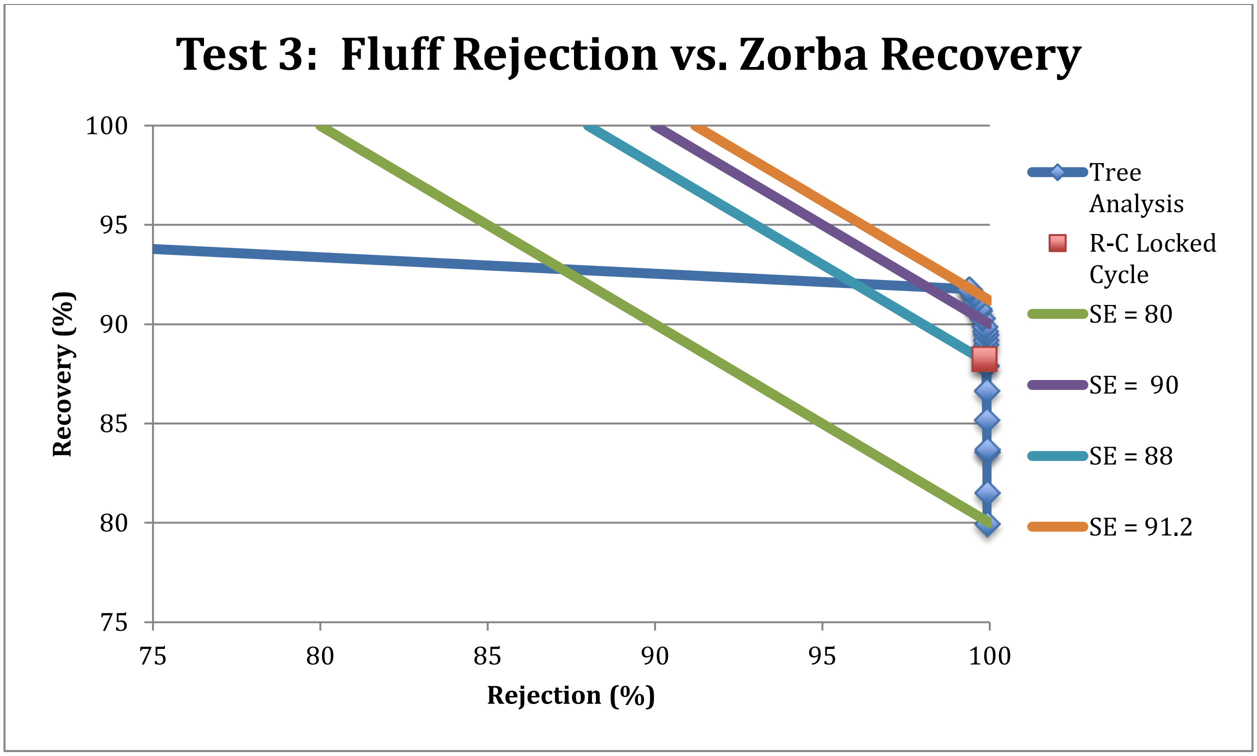


Fig. 3.35: Test 3 fluff rejection vs. zorba recovery, r-c locked cycle.

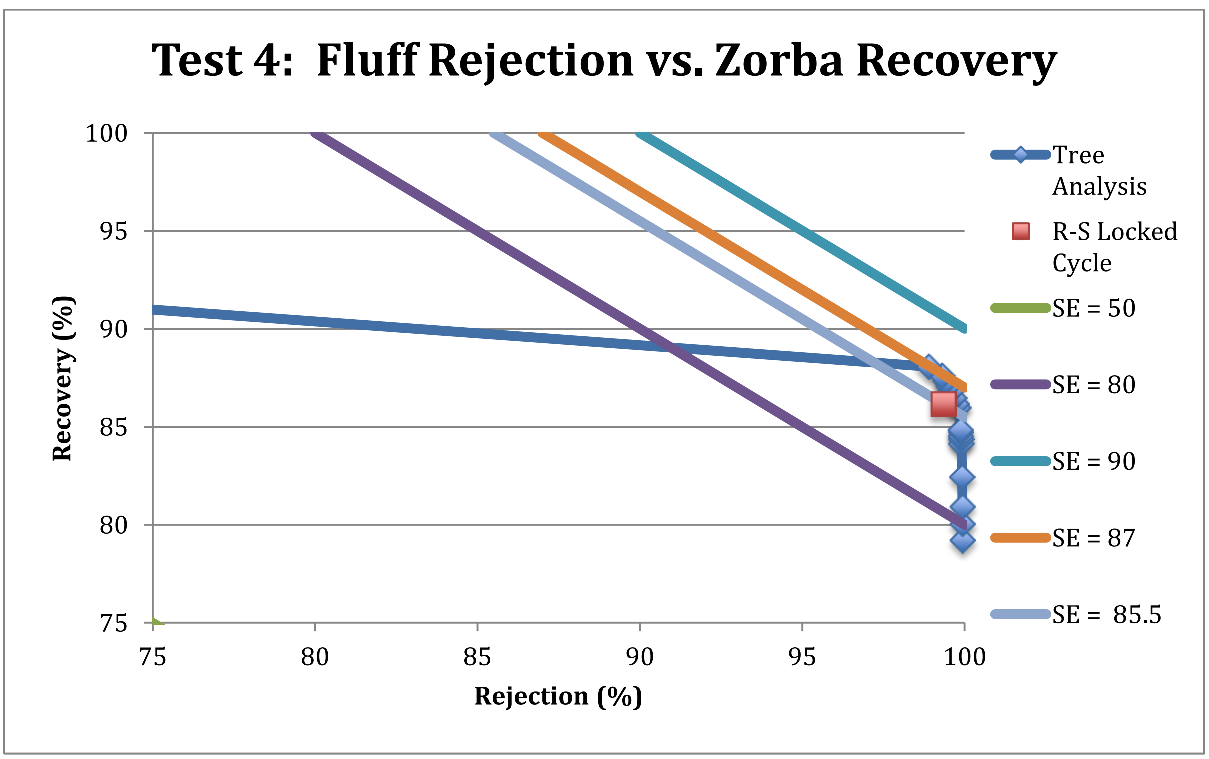


Fig. 3.36: Test 4 fluff rejection vs. zorba recovery, r-s locked cycle.

3.4.2.6 REJECTION EFFICIENCY AND RECOVERY EFFICIENCY

After theoretical efficiency was found for all of the circuits, the rejection/recovery boundary was fit with a cubic spline using the average line slope method. This gave an equation that could be used to find the difference in recovery from one point to the optimal recovery on the boundary; given both points have the same rejection. The same could be done for rejection, given both points have the same recovery. In Table 3.5 the values for "Efficient Recovery" are the maximum possible recovery, according to the rejection/recovery boundary, at the rejection that resulted from the circuit used in the test. Values for "Efficient Rejection" follow the same rules as efficient recovery, except that these values are calculated at the recovery resulting from the circuit tested. It should be noted that it is impossible to achieve both an efficient recovery and an efficient rejection at the same time, unless the circuit is operating on the boundary. Plots showing the results of circuits tested in Tests 1 through 4 are shown in Figures 3.37-3.43 along with the efficient rejection and recovery for each operating point.

Table 3.5: Shows calculations for circuits tested derived from spline fit equations.

Test Number	Description	Efficient Rejection	Efficient Recovery	Rejection Efficiency	Recovery Efficiency
Test 1	Rougher Only	99.82	89.07	99.32	96.65
Test 1	Rougher- Cleaner	99.89	87.07	99.85	95.58
Test 1	Rougher-Scavenger	99.57	89.12	99.45	98.70
Test 1	Rougher-Cleaner-Scavenger	99.78	87.76	99.83	97.52
Test 2	R-C-S Locked Cycle	99.92	91.82	99.95	99.52
Test 3	R-C Locked Cycle	99.90	89.98	99.94	98.07
Test 4	R-S Locked Cycle	99.77	87.53	99.59	98.45

Figure 3.37 shows that for the rougher only in Test 1, there could be an increase in fluff rejection at the same recovery. For the same rejection that was obtained in the rougher only test there could also be an increase in recovery. These differences are shown by the distances from the blue point, indicating the results of the test, and the two other points lying on the rejection/recovery boundary.

Figure 3.38 shows a decrease in the distance between the efficient rejection on the boundary and the rejection that resulted from the rougher-cleaner test. This would be expected from a rougher cleaner circuit. Comparing the numbers for recovery efficiency for the rougher cleaner and rougher , the rougher has a higher recovery efficiency as expected. The rejection efficiency and recovery efficiency describe how the point for a test has moved relative to the rejection/recovery boundary.

In Figure 3.39 the rejection efficiency and recovery efficiency of the rougher-scavenger test is shown, and referencing Table 3.5 it can be seen that the rejection efficiency has decreased and the recovery efficiency has increased relative to the rougher cleaner test, as one would expect. However, the rejection efficiency is greater than the rougher only when the rougher would make a better grade material. This is because as recovery gets higher, the maximum rejection gets lower. If a certain recovery number needed to be met, then the rougher may be deemed not a feasible option to use.

In Figure 3.40 the point indicating the rougher-cleaner-scavenger test appears to have a fairly high recovery efficiency and rejection efficiency. Looking at Table 3.5, the rougher-cleaner-scavenger has the second highest recovery efficiency and rejection efficiency for Test 1.

Figure 3.41 shows the results of Test 2. The rougher-cleaner-scavenger locked cycle test had the highest rejection efficiency and recovery efficiency of any of the tests. This test was the closest to the "elbow" of the curve. If this test was producing the desired fluff rejection, then it would be difficult to justify spending money on another cleaner unit.

The RCS locked cycle test also had the highest separation efficiency and the second highest theoretical efficiency. According to the tree analysis, a higher separation efficiency can be reached with the same feed and machine settings. If a higher recovery was desired, and rejection could drop a little, it would make sense to try a locked cycle test with a rougher, one cleaner, and two scavengers to see where the test point shifted along the boundary. If the desired recovery and rejection was reached, then it may be possible to justify capital expenditure for another unit.

Figure 3.42 shows a highly efficient rejection for the rougher cleaner locked cycle test. For this test, the recovery decreased, and due to the sharpness of the possible separation shown on the boundary, the recovery efficiency also decreased. It is very unlikely that a test will fall exactly on the boundary. Therefore, a test with a low recovery, even with a rejection falling next to the boundary, still has a chance of having a low rejection efficiency.

Figure 3.43 shows that the rougher-scavenger locked cycle test had a higher recovery efficiency, but a lower rejection efficiency than Test 3. Looking back at the test of the Eriez RCS system in Chapter 2, it is expected that a rougher scavenger with a recirculating load would have a lower recovery and a higher rejection than the same circuit without a recirculating load. Looking at only recovery efficiency and rejection efficiency, the rougher scavenger with the recirculating load has a higher rejection and lower recovery, relative to the bounds of the curve, than the rougher scavenger without the recirculating load.

Using recovery efficiency and rejection efficiency may be a way to compare tests that use different feed, machine settings, or assay procedures. Throughout this experiment the assay procedure changed due to the nature of doing an assay by hand. It took time for the technician to learn how to identify metals, and to do so accurately. Also after learning more about the material, more categories of material were assayed. There may be some general human error in the assays including error due to fatigue. The different quality in assays and feed could be considered noise in the data. Rejection efficiency and recovery efficiency were created in an attempt to smooth out this noise and compare the test points to what is possible instead of on an absolute scale.

When comparing tests where different tree analysis is done, it may make sense to use this method due to a change in feed or machine settings. Tests that use the same tree analysis can be compared on just grade, recovery, and rejection. When comparing circuits between tests comparing rejection efficiency and recovery efficiency, gives the same changes one would expect through circuit analysis. For example the rougher-scavenger has the highest recovery efficiency of any of the tests. The rougher-cleaner-scavenger locked cycle test also has the best combination of both efficiencies. Since this method was used just for this paper, more testing is be required in order to see if it is a valid tool for analysis.

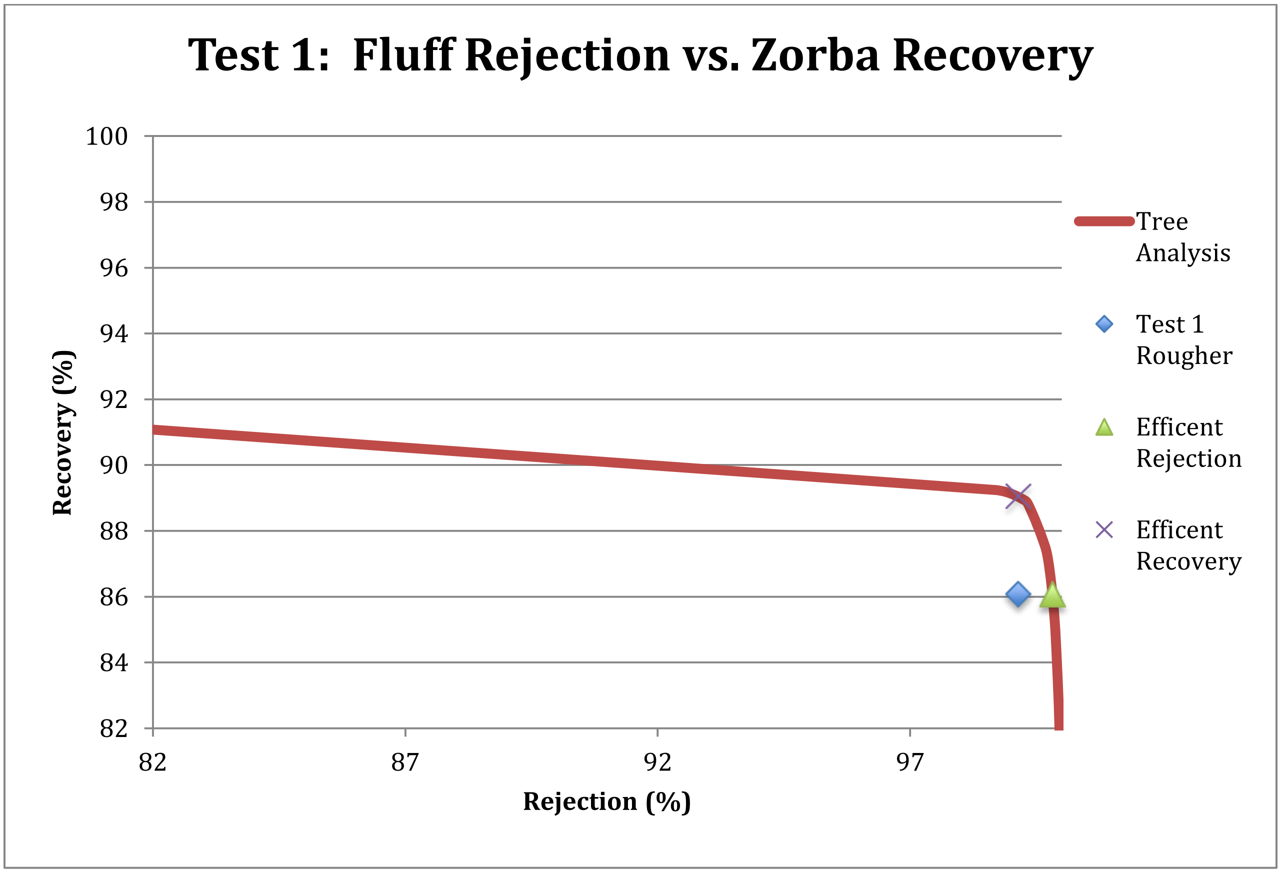


Fig. 3.37: Test 1 rejection and recovery efficiency, rougher only.

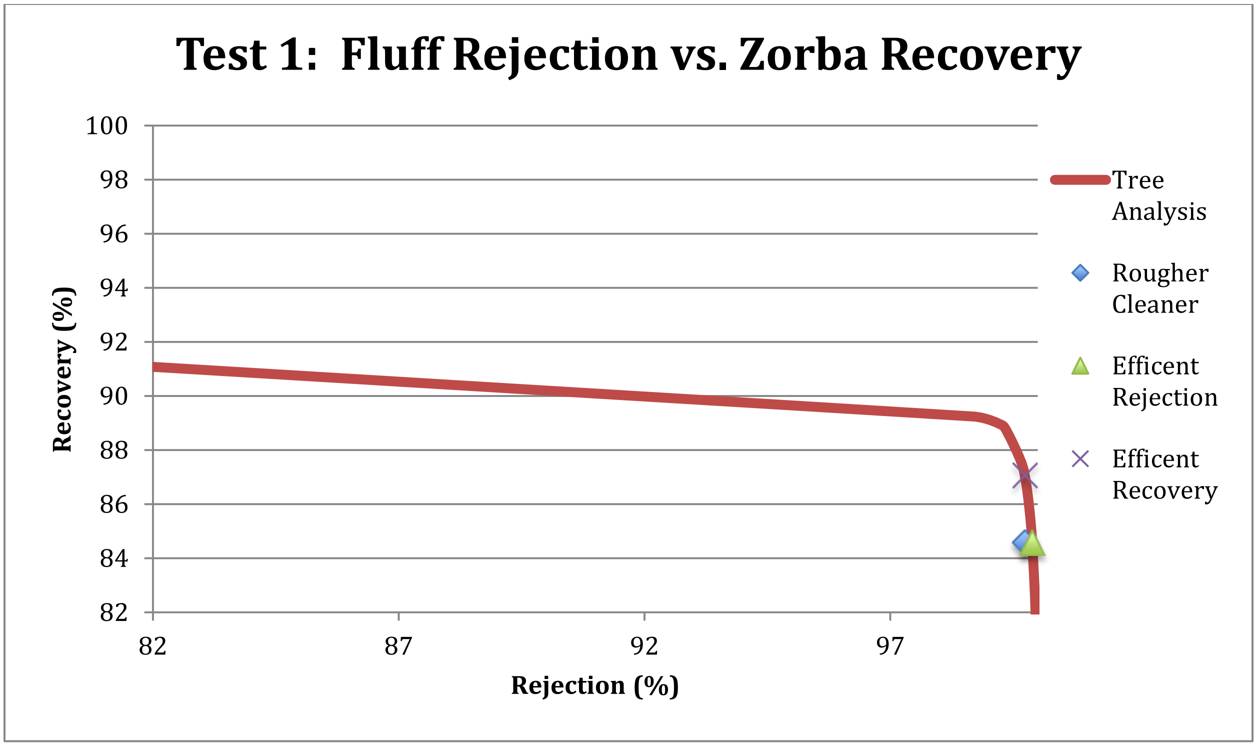


Fig. 3.38: Test 1 rejection and recovery efficiency, rougher-cleaner.

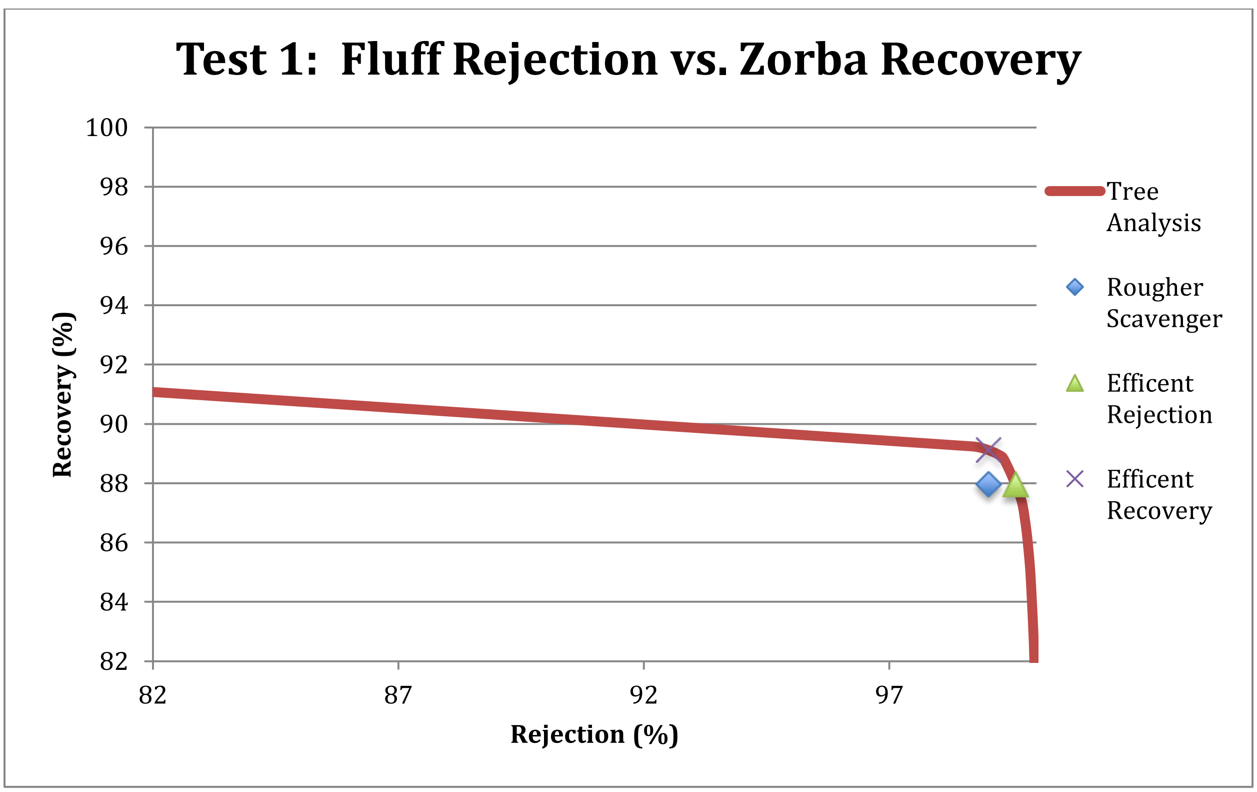


Fig. 3.39: Test 1 rejection and recovery efficiency, rougher-scavenger.

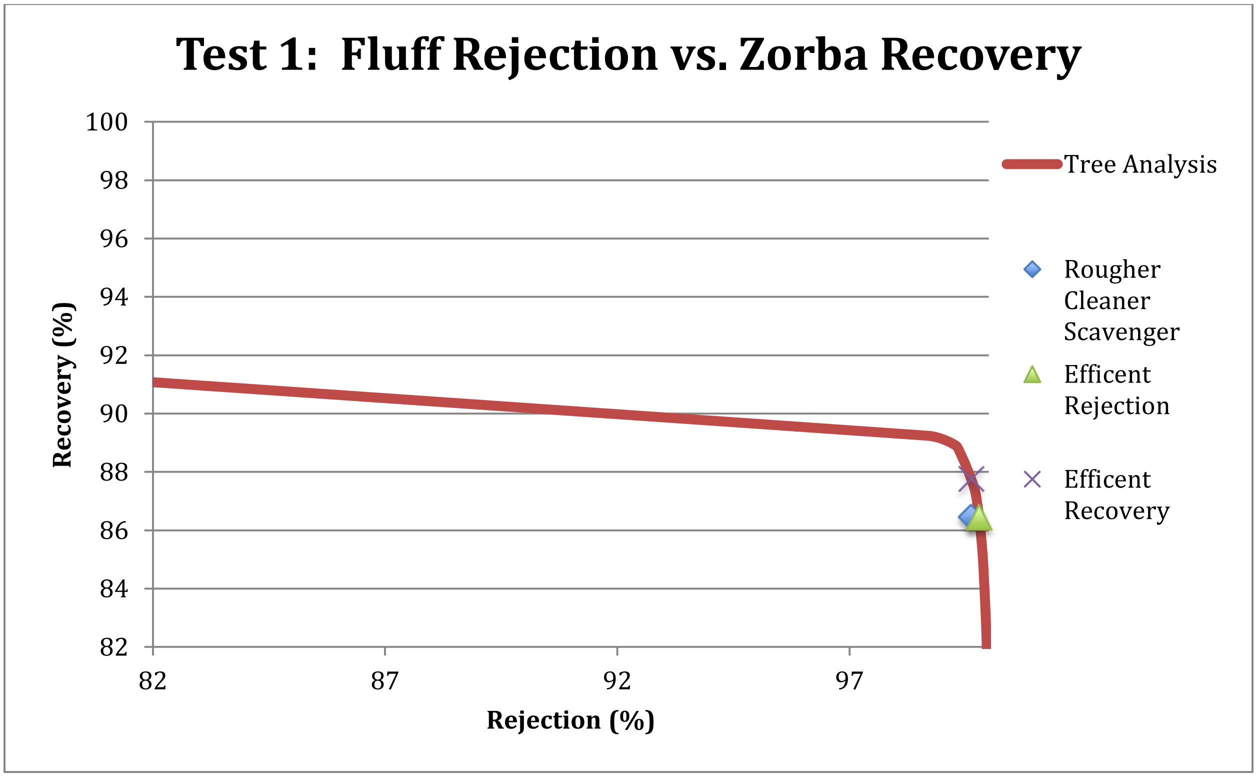


Fig. 3.40: Test 1 rejection and recovery efficiency, rougher-cleaner-scavenger.

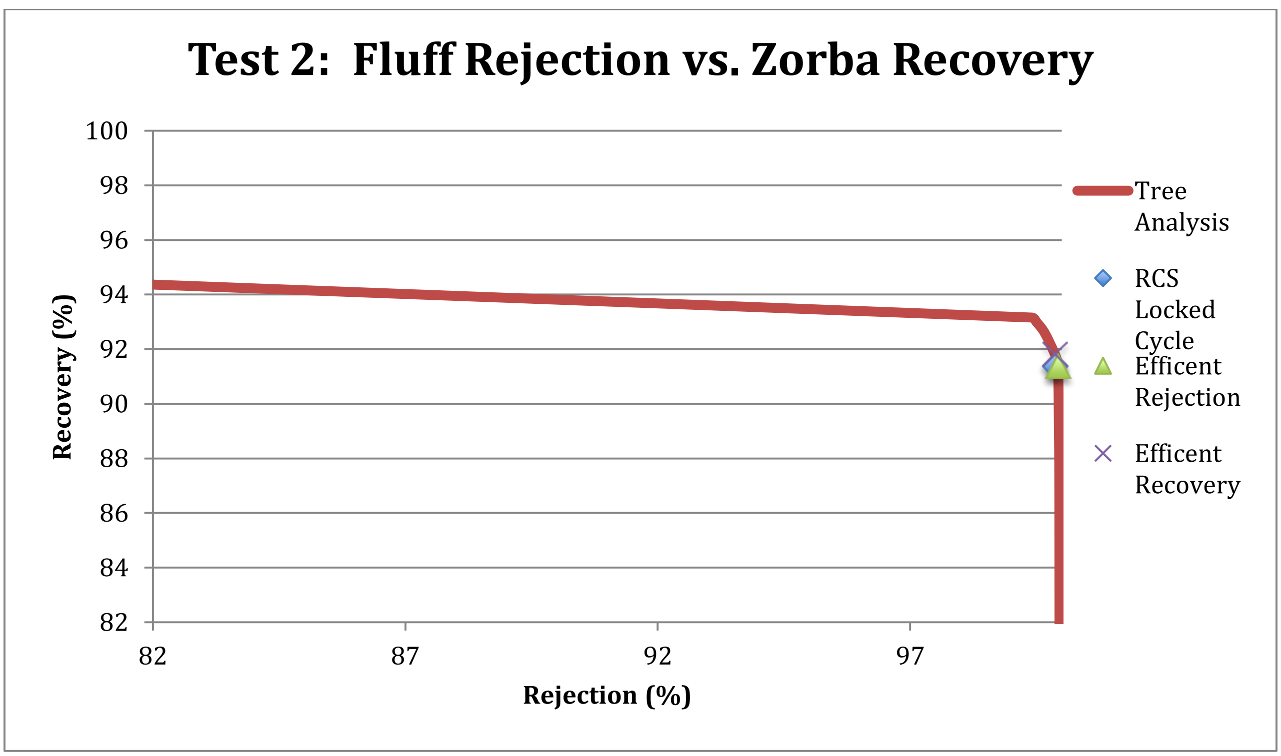


Fig. 3.41: Test 2 rejection and recovery efficiency.

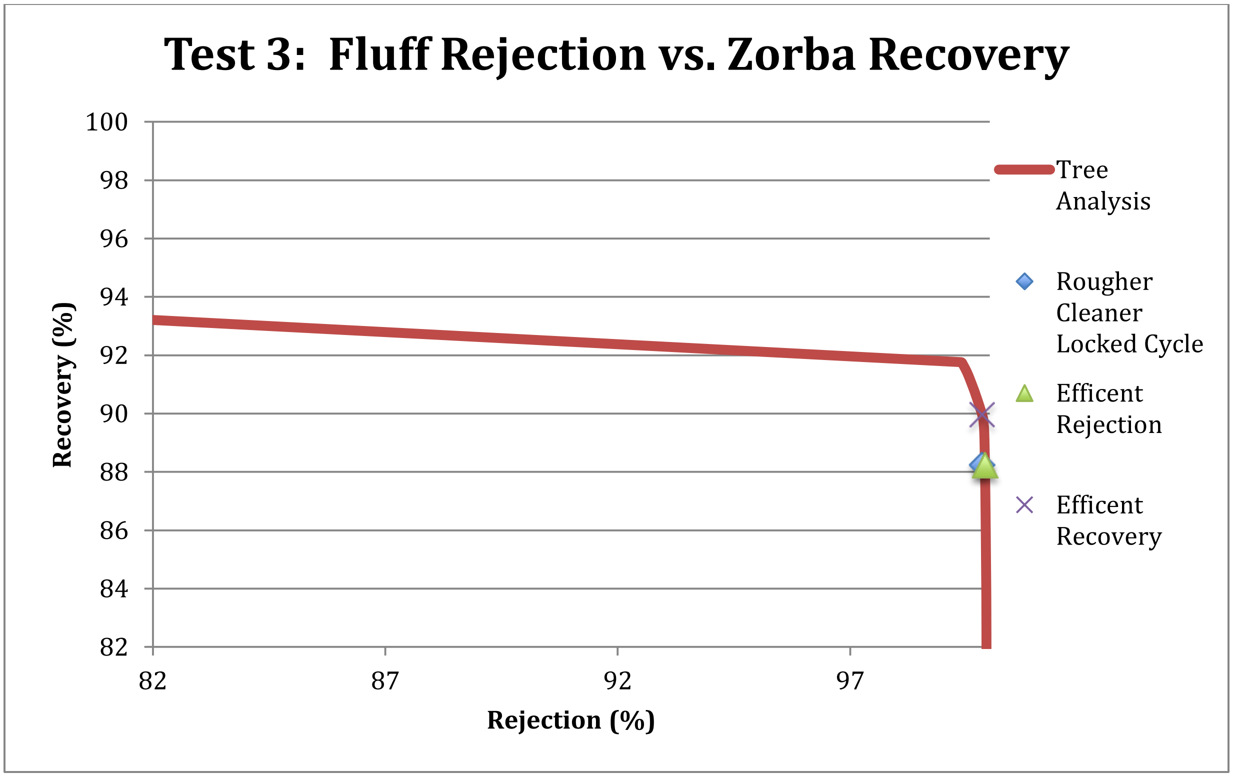


Fig. 3.42: Test 3 rejection and recovery efficiency.

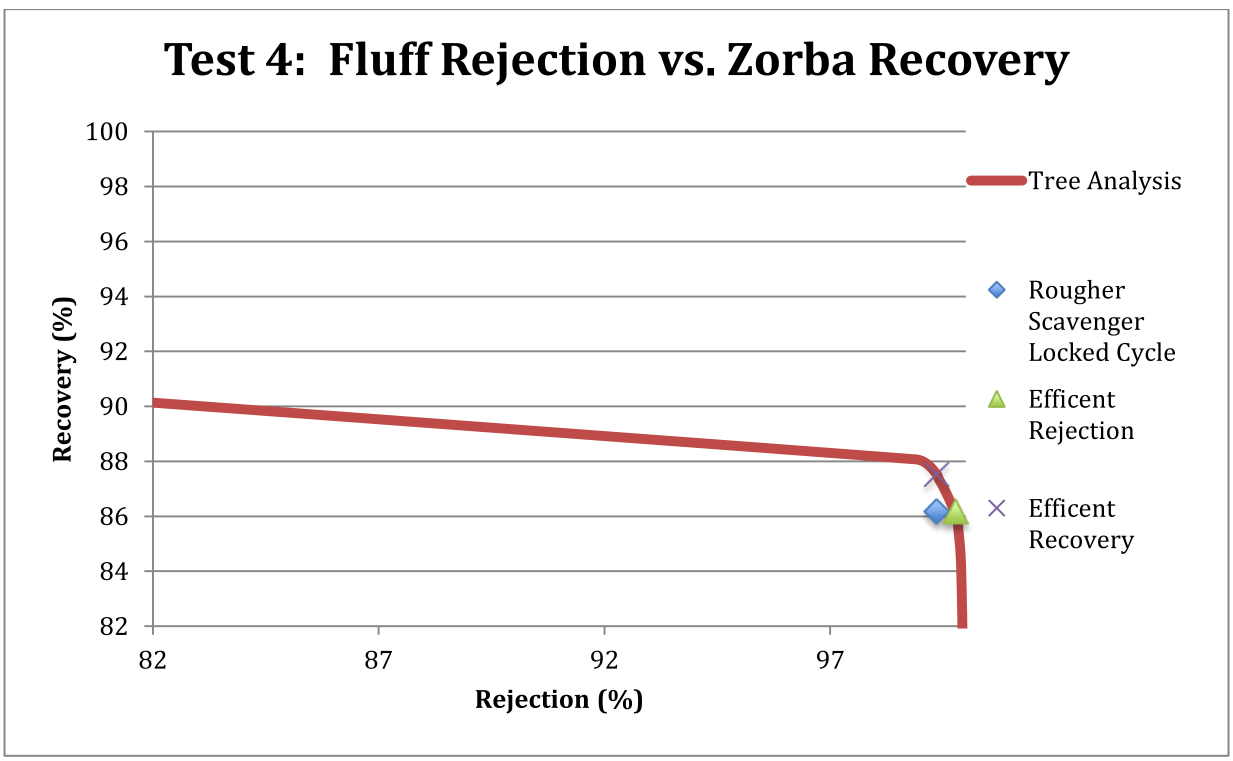


Fig. 3.43: Test 4 rejection and recovery efficiency.

3.5 SUMMARY AND CONCLUSION

Tree analysis and locked cycles tests are extremely valuable tools for judging circuit performance. If only one machine is available for testing by a manufacturer, it is possible to see how that machine may perform as part of a larger, complex circuit.

When looking at just the grade and recovery of the circuits used in the tests, not all of them perform as expected in relation to one another. In general the circuits that used a locked cycle test performed better than their counterparts that did not use a recirculating load. For example the rougher cleaner locked cycle test had a better grade and recovery than the rougher cleaner with no recirculating load. This may be due to differences in feed and assaying procedure.

Aluminum and red metals were then plotted individually to see how the circuits treated the metals differently. Overall aluminum recovery was high with the highest aluminum recovery achieved at 97.69%. The test with the highest percentage of unrecoverable aluminum was Test 4, with about 4.5% of the aluminum categorized as unrecoverable.

Red metals recovery was much lower. The highest red metals recovery achieved was 64.83% in the RCS locked cycle test. In the tree analysis for the same test showed that only 69.8% of the red metals in the feed were recoverable. Test 2 had the lowest amount of unrecoverable red metals, while Test 4 had the largest percent of unrecoverable red metals at 42.12. The percent of metals that are considered recoverable can be seen on all plots as the second leftmost point, if the range on all axis's is 0 to 100.

The plot for red metals recovery vs. red metals grade was not easy to read, so red metals grade was replaced with specific red metals grade. This calculation allowed the grade on the y-axis to represent the relationship between of red metals mass and the mass of the waste. The grade vs. recovery curves look conventional when specific grade is used, and still shows the same amount of unrecoverable metal. It may be pertinent to use aluminum and red metal plots separately, instead of zorba plots, if a processor prefers to create a product high in red metals.

When looking at all of the tests, most of the data seemed to be out of line with what would be expected in circuit analysis. However, when looking at the plots, it was apparent that the test point shifted within the grade recovery boundary in a manner that was consistent with circuit analysis. It was realized that the test points needed to be compared to their respective tree analysis.

The separation efficiency of the circuits was compared to the point with the maximum separation efficiency on the rejection/recovery boundary generated through tree analysis. The RCS locked cycle test had the highest separation efficiency, and the second highest theoretical efficiency. The rougher-scavenger in Test 1 had a lower separation efficiency, but a higher theoretical efficiency. Comparing the theoretical efficiencies may be an indicator of which circuits performed closest to the optimum point on the boundaries, but does not always fall in line with circuit analysis, and may not make sense to use if there is a high target grade.

In another proposed way or comparing a test point to its corresponding rejection/recovery boundary, recovery efficiency and rejection efficiency were compared between circuits. When these values were compared, the results fell in line with what would be expected through circuit analysis.

However, as far as the author knows this is not a method that has been used in process engineering before, and is cautious to make claims of how well it works without further testing.

Theoretical efficiency, recovery efficiency, and rejection efficiency were used in order to minimize the differences in testing due to assays, and possible material changes. These tools would be very valuable in the scrap recycling industry due to the fact that the feed to the shredder is constantly changing, and there is no standard assaying procedure. Two different yards owned by the same company could easily have different assaying procedures, and the quality of an assay can changed based on the person who is conducting the assay. Further testing should be done on these values in order to determine how useful they are.

Besides comparing circuits, tree analysis can also be used to see if machine settings need to be changed. Changing machine settings should shift the boundary created by tree analysis. Just plotting a grade vs. recovery curve is just scratching the surface of all the information that can be obtained through tree analysis. Statistical programs can be used in order to see how different machine settings shift the tree analysis boundary, if at all. Likewise could be done with changing size distributions instead of machine settings. Like many other research projects, there are more ideas and questions for this topic at the end than

REFERENCES

1. D.W. Brown, S.T. Hall, Froth flotation: preparation of a laboratory standard, Fuel, Volume 78, Issue 14, November 1999, Pages 1621-1629, ISSN 0016-2361, http://dx.doi.org/10.1016/S0016-2361(99)00108-8.

2. Pratten, S.J., Bensley, C.N. and Nicol, S.K., 1989. An evaluation of the flotation response of coals. Int. J. Miner. Process., 27: 243-262

3. Shunli Zhang, Eric Forssberg, Bo Arvidson, William Moss, Aluminum recovery from electronic scrap by High-Force® eddy-current separators, Resources, Conservation and Recycling, Volume 23, Issue 4, September 1998, Pages 225-241, ISSN 0921-3449, http://dx.doi.org/10.1016/S0921-3449(98)00022-6.

4. T.P Meloy, D.A Whaley, M.C Williams, Flotation tree analysis — reexamined, International Journal of Mineral Processing, Volume 55, Issue 1, October 1998, Pages 21-39, ISSN 0301-7516, http://dx.doi.org/10.1016/S0301-7516(98)00023-4.

CHAPTER 4: CONCLUSIONS AND RECCOMENDATIONS

Although density separation, commonly used in coal processing, has less variables than separation of zorba from shredder residue some of the same analysis techniques can be used to improve efficiency. In the Eriez RCS system it was clear that adding the cleaner and scavenger stages with a recirculating load caused a major improvement in the separation of zorba from fluff. Using circuit analysis, it is possible to meet a customers demand for high grade, without huge losses. Circuit analysis is something that should be used for all separators in a scrap yard in order to make the best use of all of the machines available.

Tree analysis is a good way to produce a grade vs. recovery curve in coal flotation, and it appears that it can also be used to analyze circuits of eddy current separators. Using tree analysis, the RCS locked cycle test had the best results in terms of combined rejection efficiency and recovery efficiency, as well as overall separation efficiency. This backs up the results found from testing the Eriez RCS system in that using a rougher, cleaner, and scavenger with a recirculating load, will give a better performance than a single rougher.

The results from the tree analysis also back up some of the expectations of circuit analysis theory stated in Chapter 2. The RCS test with no recirculation did not perform as well as the RCS Locked cycle test. Importantly, this is still true when the tests compared to their respective tree analysis curves. Circuit analysis states that there should be no difference in separation efficiency between a rougher only and an RCS system with no recirculating load. Testing in Chapter 3 showed that there was a slight improvement between using only the rougher and using the rougher-cleaner-scavenger with no recirculation. However, the RCS locked cycle test, with a recirculating load, outperformed the RCS test with no recirculating load in all measures including overall separation efficiency and theoretical efficiency. The same is true for the rougher cleaner circuit when compared to the rougher cleaner locked cycle circuit. This justifies adding recirculating streams in order to increase separation efficiency if deemed economically feasible.

The recirculating load did not improve the separation in the rougher-scavenger circuit. When looking at the tree analysis boundary for Test 4, it appears that the percentage of metals found in the feed that were deemed unrecoverable is much larger than the other tests. This may indicate a change in feed, a change in assaying procedure, or an error in conducting the test, among many other things. There are reasons to believe that the feed for Test 4 contained a larger fraction of small, difficult to recover, particles than previous tests, which may have made the rougher scavenger locked cycle test perform worse than its counterpart in Test 1, even when compared to the tree analysis boundary.

Further testing has to be done on tree analysis, but if it is used in the field testing standards have to be introduced. These standards should include, but are not limited to:

- A known and specific list of materials to be assayed for.
- A minimum assay size. Particles with a size less than a determined diameter should not be counted in the assay at all.

- A branch in the tree analysis should stop when the mass of a sample is less than a specified percentage of the mass of the feed.

Other standardizing methods that can be used for testing circuits or machine settings would be the creation of a synthetic feed material that could have a known and exact contents and size distribution.

The creation of standards was one of the goals of this research. Throughout the testing, researchers involved gained a better understanding of sample size, and sampling technique. Standard names and calculations have been introduced, yet not completely accepted, through the test work that has been completed. Future standards, such as the standards for tree analysis, have been conceived yet not completely realized.

After this testing has been completed, there are more questions about recycling and eddy current separators than in the beginning of the test work. More testing should be done on tree analysis and variations of tree analysis. It is especially important to see if changing machine settings can shift the tree analysis boundary.

It is apparent through this research that a lack of a standard assay and small sample sizes can skew recovery statistics reported. Other goals for this research also have not been met, but may be met in the future.

APPENDIX A: TESTING OF ERIEZ RCS SYSTEM

Test Plan:

RCS System:

		Percent of feed recirculating from	
Test Number	Target Feed Rate (tph)	Cleaner (%)	Scavenger (%)
Test 1	3.25	10	30
Test 3	5	5	15
Test 4	1.5	5	30
Test 6	3.25	5	15
Test 8	3.25	5	15
Test 10	3.25	5	15
Test 12	5	10	15
Test 13	1.5	10	15
Test 16	5	5	30
Test 17	3.25	5	15
Test 18	3	20	20

Rougher Only:

Test	Splitter Distance from Belt (in)	Tumbleback Motor Frequency (Hz)
1	3.25	9
5	4	16
6	4	9
7	4.75	16
8	4.75	9
2	3.25	16
4	4	23

Assay Results:

RCS System

	Zorba Contents		Tailings Contents	
Test	Metal (g)	Fluff (g)	Metal (g)	Fluff (g)
1	57608	1041	2434	631854.2
3	43091.3	376.8	9612	613166.166
4	34926.6	257.2	1378.921	334751
6	43045.92	442	4308	561547.4
8	39524	365	1414	503033.9
10	31987	349	932	368771
12	46773	994	3270	655441
13	37648.2	836	508	457221.1
16	61035.3893	1211.092	3762	685831.7
17	62798	693	4290	665420

Rougher Only

	Zorba Contents		Tailings Contents	
Test	Metal (g)	Fluff (g)	Metal (g)	Fluff (g)
1	46878	30637	2371	422748
2	45041.72	39462.5	3889	496423.4
4	63625	23586.8	9531	816919.9
5	68123	27729	6948	782755.2811
6	80687	16356.541	8418	900127.5
7	65558	7711	16644	882829
8	72240	6231.5	14844	2126.27

Feed Rates Calculated:

RCS System

Test	Time (min)	Feed Rate (tph)	Total Feed (lb)	Total Feed (tons)	Volume (ft^3)
1	42	3.8	5320.000	2.660	161.212
3	42	3.9	5460.000	2.730	165.455
4	83.3	2.025	5622.750	2.811	170.386
6	42	3.33	4662.000	2.331	141.273
8	42	2.99	4186.000	2.093	126.848
10	42	2.2	3080.000	1.540	93.333
12	31.5	5.17	5428.500	2.714	164.500
13	84	1.36	3808.000	1.904	115.394
16	31.5	5.46	5733.000	2.867	173.727
17	42	4	5600.000	2.800	169.697
		Total	48900.250	24.450	1481.826
		Average	4890.025	2.445	148.183

Rougher Only

Test	Time (min)	Feed Rate (tph)	Total Feed (lb)	Total Feed (tons)	Volume (ft^3)
1	42	2.7	3780.000	1.890	114.545
2	31.5	4.3	4515.000	2.258	136.818
5	42	4.87	6818.000	3.409	206.606
6	84	2.77	7756.000	3.878	235.030
7	42	5.32	7448.000	3.724	225.697
8	84	2.9	8120.000	4.060	246.061
		Total	38437.000	19.219	1164.758
		Average	6406.167	3.203	194.126

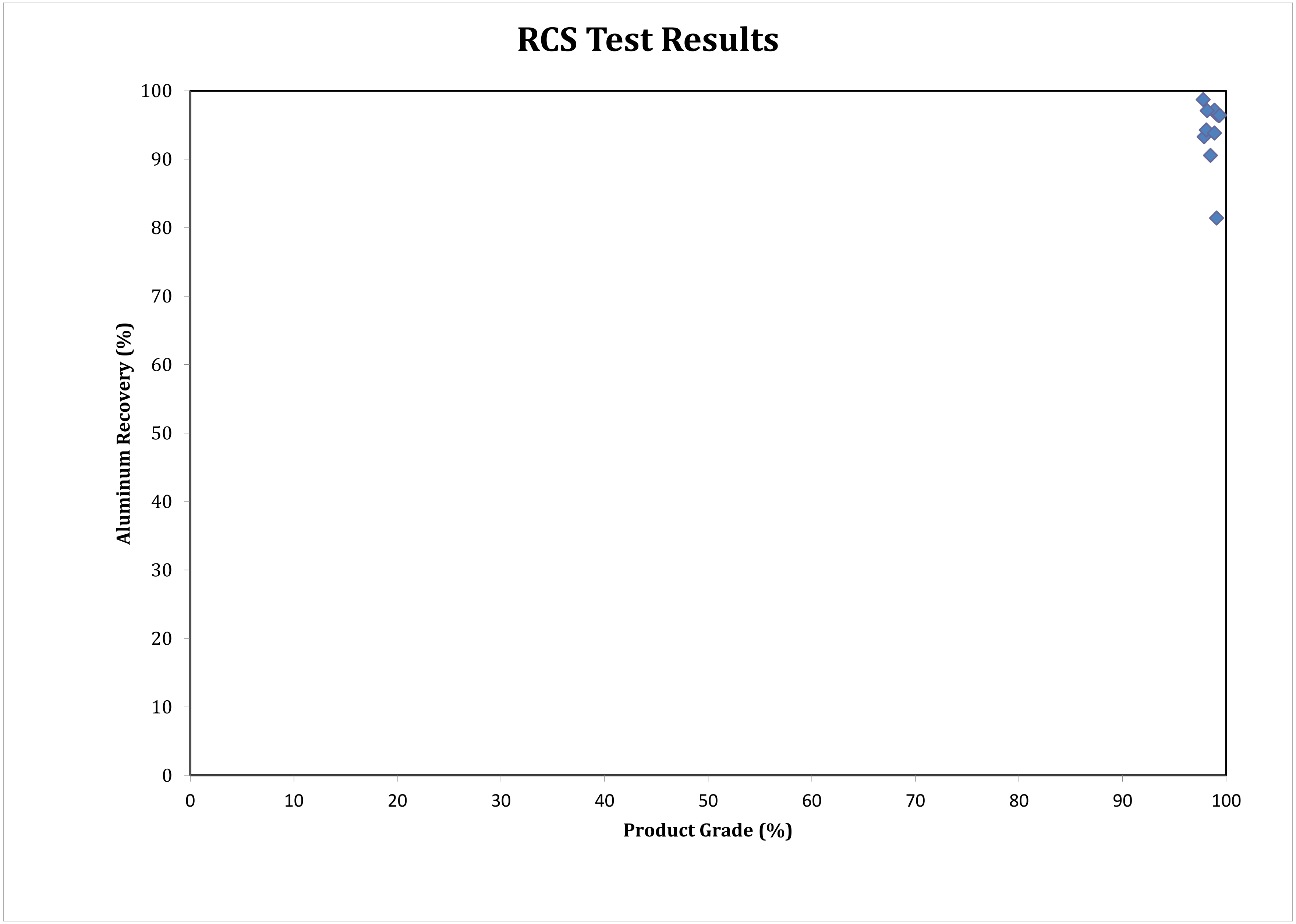
Results:

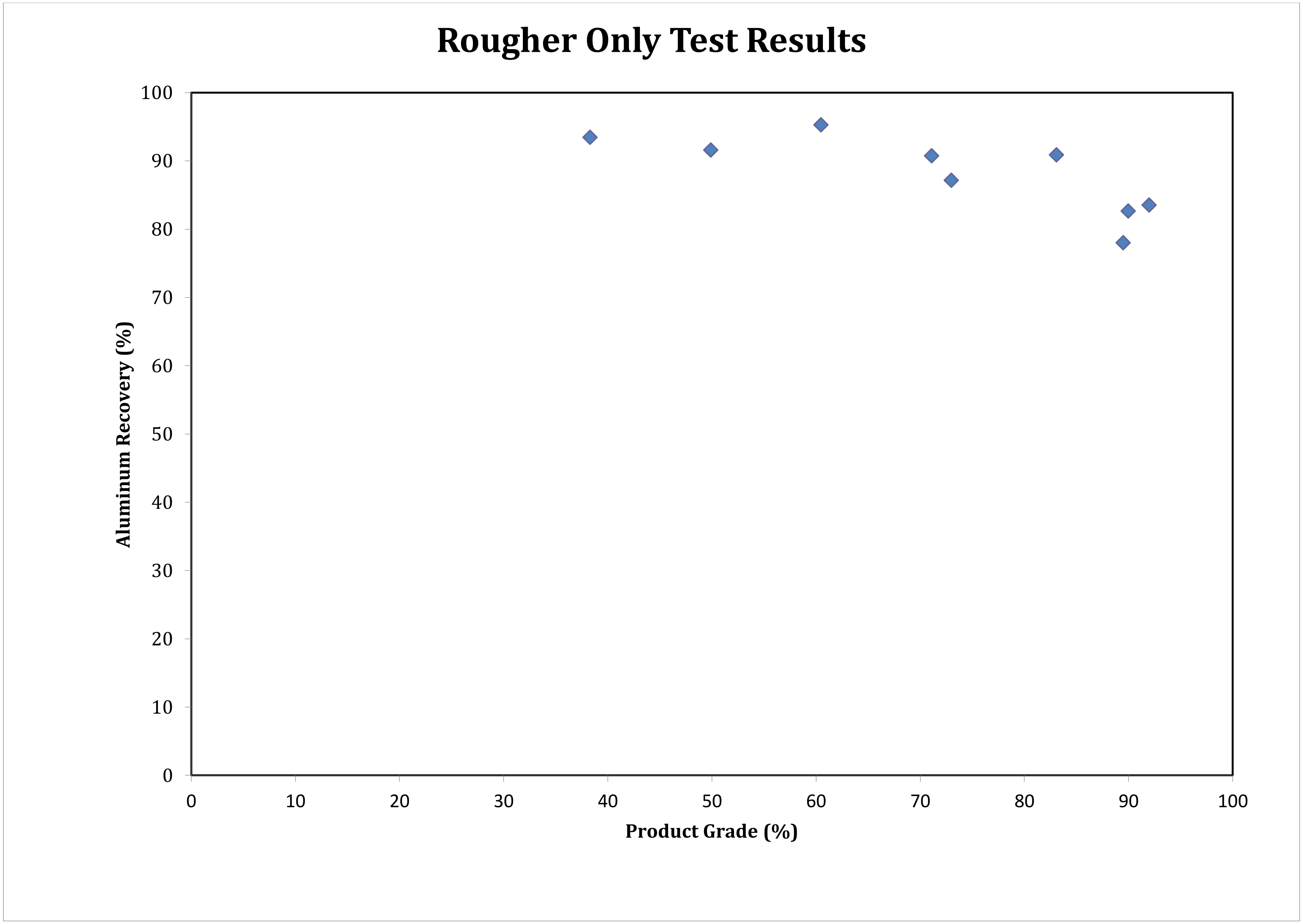
RCS System

Test Number	Feed Grade (%)	Grade of Tailings (%)	Yield to Zorba (%)	Zorba Grade (%)	Al Recovery (%)	Fluff Rejection (%)
Test 1	8.433	0.269	8.337	98.195	97.077	99.836
Test 3	7.941	1.581	6.522	99.098	81.388	99.936
Test 4	9.762	0.394	9.473	99.285	96.345	99.925
Test 6	7.744	0.787	7.120	98.499	90.555	99.884
Test 8	7.545	0.280	7.352	99.100	96.562	99.928
Test 10	8.076	0.249	7.934	98.897	97.157	99.905
Test 12	6.971	0.502	6.642	97.902	93.275	99.850
Test 13	7.694	0.110	7.763	97.799	98.682	99.815
Test 16	8.702	0.544	8.363	98.093	94.271	99.825
Test 17	9.243	0.628	8.767	98.889	93.797	99.893
Test 18	8.140	0.319	7.894	99.396	96.392	99.948

Rougher Only

Test	Feed Grade (%)	Grade of Tailings (%)	Yield To Zorba (%)	Zorba Grade (%)	Al Recovery (%)	Fluff Rejection (%)
1	9.819	0.549	15.464	60.491	95.273	93.225
2	7.874	0.777	14.449	49.899	91.563	92.142
3	9.165	0.776	22.360	38.296	93.429	84.811
4	8.073	1.148	9.638	72.998	87.154	97.169
5	8.367	0.869	10.677	71.097	90.720	96.632
6	8.911	0.901	9.746	83.093	90.877	98.191
7	7.778	1.834	6.780	89.499	78.015	99.228
8	8.299	1.480	7.534	91.996	83.510	99.342


RCS Test Results
Aluminum Recovery (%)
Product Grade (%)
0
10
20
30
40
50
60
70
80
90
100


Rougher Only Test Results
Aluminum Recovery (%)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
Product Grade (%)

APPENDIX B: RAW DATA FOR TREE ANALYSIS TESTS

Test 1:

Sample	Al Mass Total (g)	Cu (g)	Brass (g)	ICW (g)	Fluff (g)	Circuit Boards (g)	Aluminum Wire Only (g)
TTT,TTT	434.93	873.02	55.15	2328.64	213748.46	N/A	N/A
TTT,TTC	22.6	10.21	0	Counted in Cu	140.48	N/A	N/A
TT,TTC	36.63	66.03	0	Counted in Cu	171.58	N/A	N/A
T,TTC	42.51	86.9	0	Counted in Cu	203.09	N/A	N/A
TTC	43.57	128.56	0	Counted in Cu	211.92	N/A	N/A
TCT	21.85	292.58	0	Counted in Cu	181.14	N/A	N/A
TCC	58.17	273.63	0	Counted in Cu	75.71	N/A	N/A
CTT	31.65	74.43	0	Counted in Cu	1253.61	N/A	N/A
CTC	345.46	65.22	0	Counted in Cu	45.63	N/A	N/A
CCT	29.63	104.2	0	Counted in Cu	253.7	N/A	N/A
C,CCT	330.02	50.8	0	Counted in Cu	140.4	N/A	N/A
CC,CCT	402.69	143.1	0	Counted in Cu	96.84	N/A	N/A
CCC,CCT	302.17	77.78	0	Counted in Cu	42.52	N/A	N/A
CCC,CCC	22998.02	2441.51	2146.92	Counted in Cu	37.59	N/A	N/A

Coning and quartering assay

Sample	Al Mass (g)	Cu (g)	Brass (g)	ICW (g)	Fluff (g)	Circuit Boards(g)	Aluminum Wire (g)
TTT,TTT	59.23	118.89	7.51	317.12	29108.81301	Not Assayed	Not Assayed

Sample	Mass Assayed (g)	Total Sample Mass (g)	% Assayed
TTT,TTT	29676.52301	217917.20	13.62

Test 2:

Sample	Al Mass Total (g)	Cu (g)	Brass (g)	ICW (g)	Fluff (g)	Circuit Boards (g)	Aluminum Wire Only (g)
TTT,TTT	489.64	1570.11	0.00	3109.27	215730.29	N/A	N/A
TTT,TTC	22.60	20.72	0.00	4.23	169.67	N/A	N/A
TT,TTC	36.63	27.27	0.00	0.73	163.69	N/A	N/A
T,TTC	42.51	45.36	2.67	2.97	178.53	N/A	N/A
T,TCT	43.57	26.48	0.00	14.90	219.64	N/A	N/A
T,TCC	21.85	21.22	0.00	2.21	8.50	N/A	N/A
TCT	58.17	48.67	9.05	6.58	205.18	N/A	N/A
TCC	55.10	46.97	8.03	7.31	16.54	N/A	N/A
CTT	34.23	17.64	0.00	3.21	79.05	N/A	N/A
C,TCT	20.20	7.11	10.10	0.00	6.68	N/A	N/A
C,TCC	506.93	28.10	96.92	0.00	0.00	N/A	N/A
C,CTT	31.65	8.50	0.00	18.53	29.46	N/A	N/A
C,CTC	345.46	30.68	89.19	0.52	0.00	N/A	N/A
CC,CTT	29.63	8.16	0.00	1.12	14.93	N/A	N/A
CC,CTC	330.02	59.78	23.45	7.21	0.00	N/A	N/A
CC,CCT	402.69	37.03	21.20	8.33	10.25	N/A	N/A
CCC,CCT	302.17	28.81	8.98	0.00	13.40	N/A	N/A
CCC,CCC	22138.46	1996.71	894.48	45.36	57.15	N/A	N/A

Coning and quartering assay

Sample	Al Mass (g)	Cu (g)	Brass (g)	ICW (g)	Fluff (g)	Circuit Boards(g)	Aluminum Wire (g)
TTT,TTT	66.29	212.57	0	420.95	29206.788 88	Not Assayed	Not Assayed

Sample	Mass Assayed (g)	Total Sample Mass (g)	% Assayed
TTT,TTT	29906.59888	220899.30	13.54

Test 3:

Sample	Al Mass Total (g)	Cu (g)	Brass (g)	ICW (g)	Fluff (g)	Circuit Boards (g)	Aluminum Wire Only (g)
TTT,TTT	832.61	1832.66	48.16	3146.43	221843.33	268.30	N/A
TTT,TTC	66.77	27.77	1.00	4.17	164.46	0.48	8.83
TT,TTC	89.86	34.37	0.00	8.26	170.23	2.41	0.00
T,TTC	85.75	52.53	3.16	11.35	168.89	2.29	0.00
T,TCT	75.19	37.59	8.02	10.88	186.51	2.18	11.34
T,TCC	63.30	27.77	1.00	4.17	9.88	1.18	8.90
T,CTT	53.40	30.04	3.57	8.51	191.91	0.95	7.09
T,CTC	41.56	20.71	7.14	0.70	6.59	0.33	6.89
T,CCT	51.33	21.59	5.10	14.20	25.00	0.75	5.28
T,CCC	250.26	80.65	21.32	7.54	16.54	1.31	18.94
C,TTT	14.75	3.63	2.53	10.51	66.71	0.00	1.11
C,TTC	15.73	2.15	23.42	0.00	0.19	0.50	0.93
C,TCT	38.05	8.55	7.31	2.04	15.28	0.00	1.09
C,TCC	410.63	31.13	72.80	1.13	0.03	2.60	4.90
C,CTT	26.60	7.73	2.75	0.07	53.96	0.67	0.00
C,CTC	526.18	40.18	108.43	0.00	0.30	7.34	4.28
C,CCT	366.36	30.15	22.43	5.60	16.58	1.57	9.45
CC,CCT	447.24	26.25	16.27	0.87	17.15	0.00	0.00
CCC,CCT	347.75	49.27	85.04	0.00	19.43	0.00	0.00
CCC,CCC	23072.41	2021.21	1249.19	31.75	59.88	59.87	0.00

Coning and quartering assay

Sample	Al Mass (g)	Cu (g)	Brass (g)	ICW (g)	Fluff (g)	Circuit Boards(g)
TTT,TTT	135.89	299.11	7.86	513.53	36207.16493	43.79

Sample	Mass Assayed (g)	Total Sample Mass (g)	% Assayed
TTT,TTT	37163.55493	227703.18	16.32

Test 4:

Sample	Al Mass Total (g)	Cu (g)	Brass (g)	ICW (g)	Fluff (g)	Circuit Boards (g)	Aluminum Wire Only (g)
TTT,TTT	1196.87	2584.12	136.45	3913.79	223047.10	466.38	132.57
TTT,TTC	44.88	32.00	3.61	12.52	177.15	1.42	9.44
TT,TTC	46.96	41.69	0.12	1.72	183.76	1.32	8.17
T,TTC	60.24	47.23	2.33	12.24	208.64	0.73	13.01
T,TCT	54.64	43.68	2.24	7.35	178.95	2.28	10.07
T,TCC	26.74	17.40	0.00	0.00	9.08	0.60	7.84
T,CTT	48.80	41.15	2.65	7.42	217.59	1.31	6.70
T,CTC	18.35	14.45	2.80	1.68	5.69	2.15	5.40
T,CC	42.03	29.72	0.26	3.58	11.25	1.92	8.49
C,TTT	86.69	63.68	0.00	69.27	885.33	9.86	6.68
C,TTC	57.40	16.11	1.76	2.73	9.86	0.21	3.11
C,TC	240.69	46.47	4.89	2.56	11.82	1.76	7.65
C,CTT	37.64	26.16	1.04	11.38	103.04	2.20	2.12
C,CTC	207.92	55.20	11.80	3.21	1.01	3.28	5.28
C,CCT	498.56	41.93	20.20	12.39	34.81	7.50	7.50
CC,CCT	282.67	30.79	59.66	3.97	156.15	1.71	4.67
CCC,CCT	451.50	38.27	5.86	1.86	26.87	1.04	7.58
CCC,CCC	22978.06	1517.72	1515.00	31.75	32.66	59.87	70.76

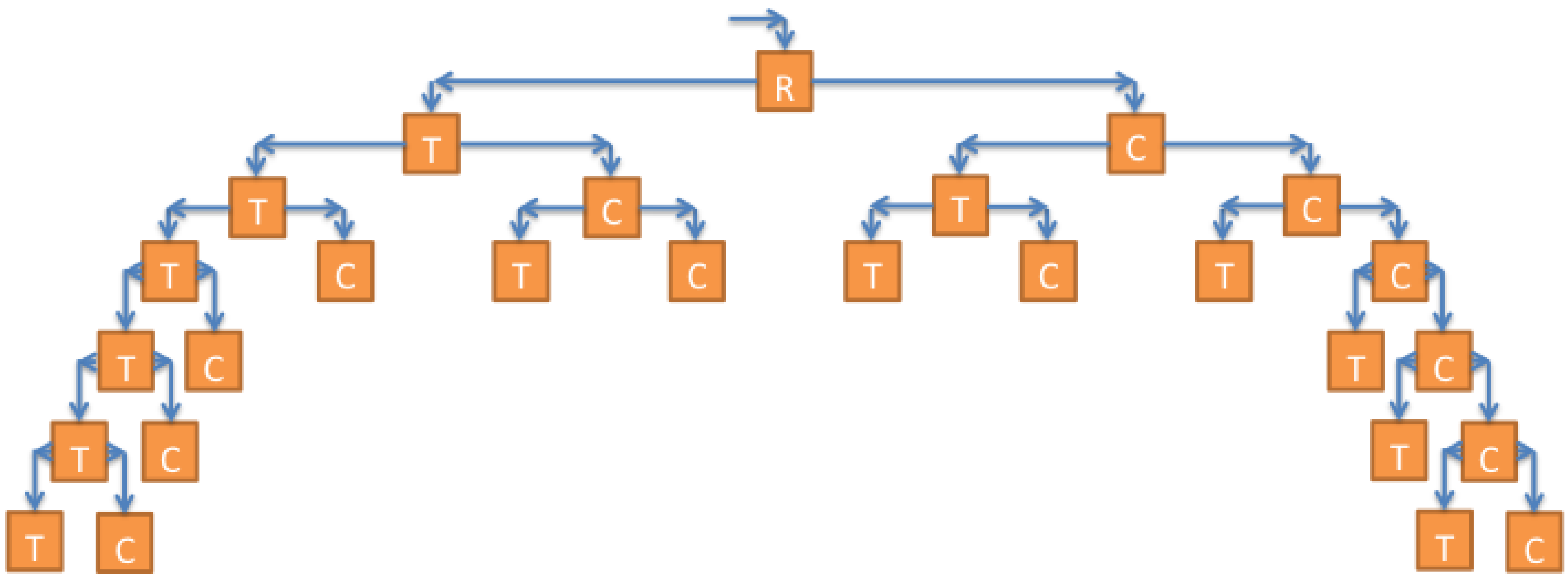
Coning and quartering assay

Sample	Al Mass (g)	Cu (g)	Brass (g)	ICW (g)	Fluff (g)	Circuit Boards(g)
TTT,TTT	197.27	425.92	22.49	645.08	36763.11196	76.87

Sample	Mass Assayed (g)	Total Sample Mass (g)	% Assayed
TTT,TTT	38053.87196	230878.33	16.48

APPENDIX C: TREE ANALYSIS DATA FOR TEST 1

Tree Sample Diagram

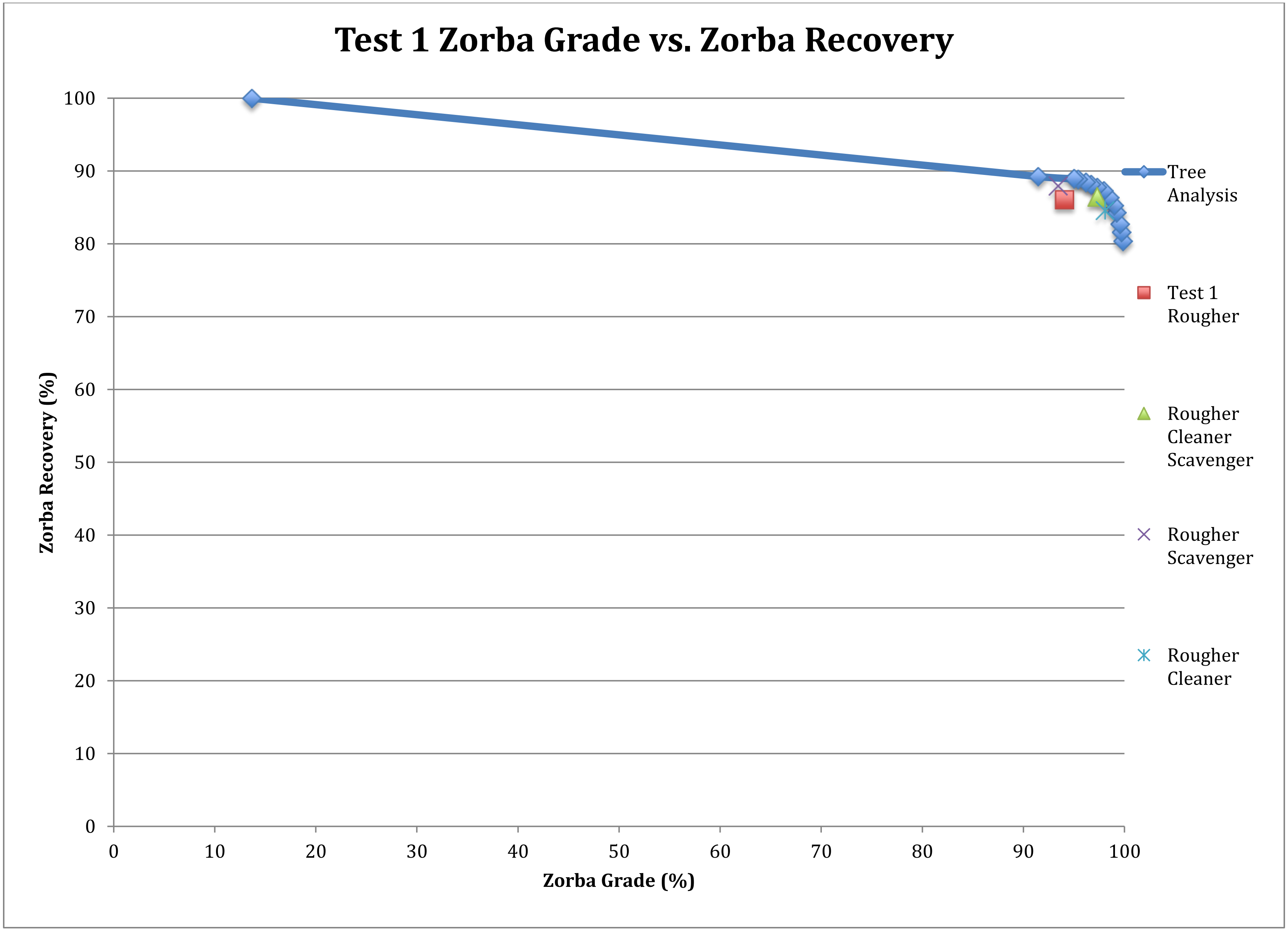


Zorba Grade and Recovery:

Sample	Reds Mass (g)	Fluff Mass (g)	Zorba Metals (g)	Total Mass (g)
TTT,TTT	3256.804642	213748.4608	3691.73551	217440.1963
TTT,TTC	10.21	140.48	32.81	173.29
TT,TTC	66.03	171.58	102.66	274.24
T,TTC	86.9	203.09	129.41	332.5
TTC	128.56	211.92	172.13	384.05
TCT	292.58	181.14	314.43	495.57
TCC	273.63	75.71	331.8	407.51
CTT	74.43	1253.61	106.08	1359.69
CTC	65.22	45.63	410.68	456.31
CCT	104.2	253.7	133.83	387.53
C,CCT	50.8	140.4	380.82	521.22
CC,CCT	143.1	96.84	545.79	642.63
CCC,CCT	77.78	42.52	379.95	422.47
CCC,CCC	4588.43	37.59	27586.45158	27624.04158

Sample	Zorba Grade (%)	Total Mass (g)	Zorba Mass (g)	Zorba Yield (%)	Cumulative Grade (%)	Cumulative Zorba Mass (%)
CCC,CCC	99.8639	27624.0416	27586.4516	80.3834	99.8639	80.3834
CTC	90.0002	456.3100	410.6800	1.1967	99.7036	81.5801
CCC,CCT	89.9354	422.4700	379.9500	1.1071	99.5589	82.6872
CC,CCT	84.9307	642.6300	545.7900	1.5904	99.2363	84.2776
TCC	81.4213	407.5100	331.8000	0.9668	98.9907	85.2444
C,CCT	73.0632	521.2200	380.8200	1.1097	98.5413	86.3541
TCT	63.4482	495.5700	314.4300	0.9162	97.9724	87.2703
TTC	44.8197	384.0500	172.1300	0.5016	97.3129	87.7719
T,TTC	38.9203	332.5000	129.4100	0.3771	96.6924	88.1489
TT,TTC	37.4344	274.2400	102.6600	0.2991	96.1774	88.4481
CCT	34.5341	387.5300	133.8300	0.3900	95.4297	88.8380
TTT,TTC	18.9336	173.2900	32.8100	0.0956	95.0170	88.9336
CTT	7.8018	1359.6900	106.0800	0.3091	91.4751	89.2427
TTT,TTT	1.6978	217440.1963	3691.7355	10.7573	13.6770	100.0000

Circuit	Grade (%)	Recovery (%)
Rougher Only	94.046	86.086
Rougher Cleaner	98.071	84.581
Rougher Scavenger	93.418	87.969
Rougher Cleaner Scavenger	97.286	86.464

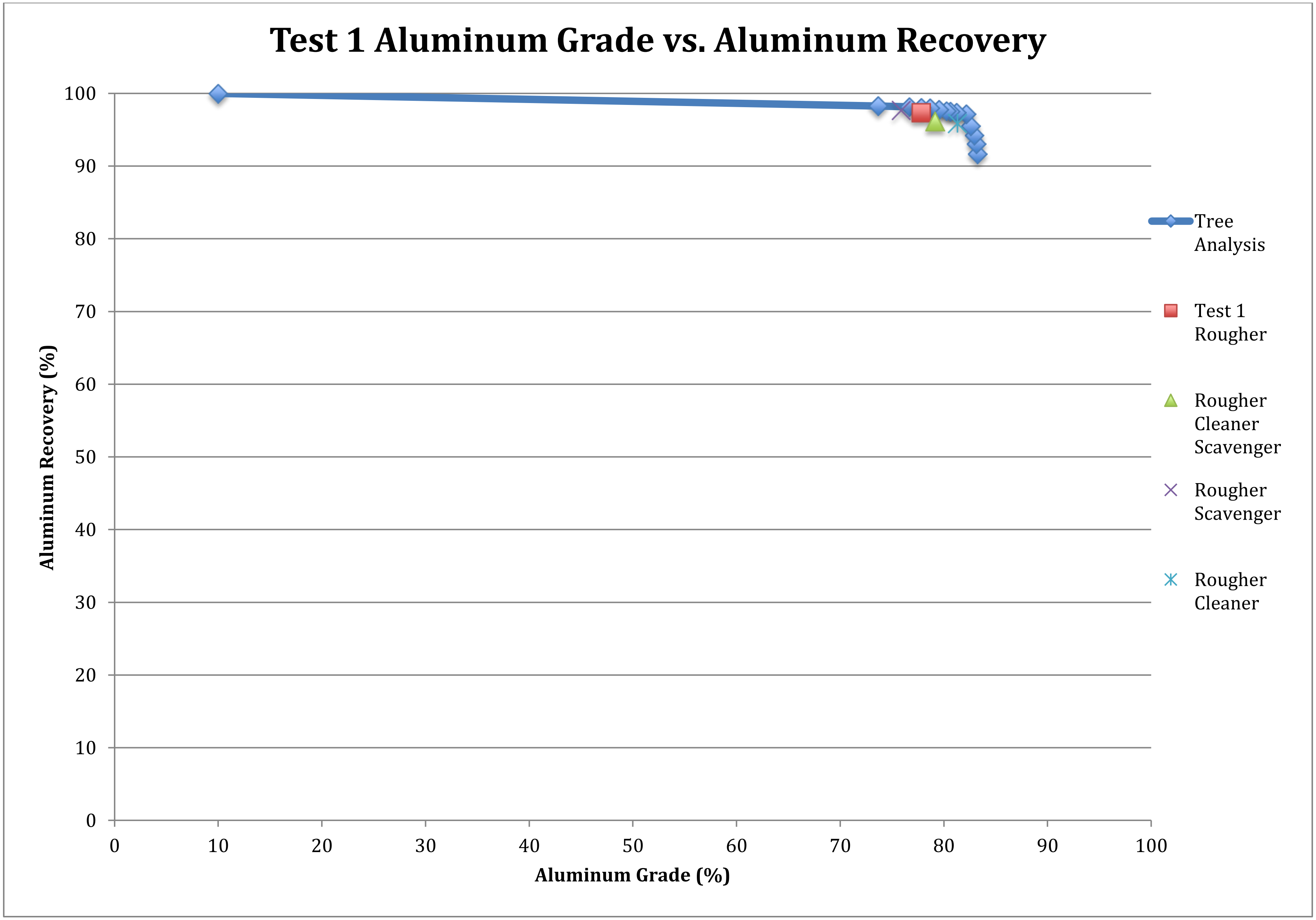

Test 1 Zorba Grade vs. Zorba Recovery
100
90
80
70
60
50
40
30
20
10
0
Zorba Recovery (%)
0
10
20
30
40
50
60
70
80
90
100
Zorba Grade (%)
Tree Analysis
Test 1 Rougher
Rougher Cleaner Scavenger
Rougher Scavenger
Rougher Cleaner

Aluminum Grade and Recovery:

Sample	Al Mass (g)	Fluff Mass (g)	Total Mass (g)	Aluminum Grade (%)
TTT,TTT	434.931	213748.461	217440.196	0.200
TTT,TTC	22.600	140.480	173.290	13.042
TT,TTC	36.630	171.580	274.240	13.357
T,TTC	42.510	203.090	332.500	12.785
TTC	43.570	211.920	384.050	11.345
TCT	21.850	181.140	495.570	4.409
TCC	58.170	75.710	407.510	14.274
CTT	31.650	1253.610	1359.690	2.328
CTC	345.460	45.630	456.310	75.707
CCT	29.630	253.700	387.530	7.646
C,CCT	330.020	140.400	521.220	63.317
CC,CCT	402.690	96.840	642.630	62.663
CCC,CCT	302.170	42.520	422.470	71.525
CCC,CCC	22998.022	37.590	27624.042	83.254

Sample	Al Grade (%)	Total Mass (g)	Al Mass (g)	Al Yield (%)	Cumulative Grade (%)	Cumulative Al Mass (%)
CCC,CCC	83.254	27624.042	22998.022	91.626	83.254	91.626
CTC	75.707	456.310	345.460	1.376	83.131	93.002
CCC,CCT	71.525	422.470	302.170	1.204	82.959	94.206
C,CCT	63.317	521.220	330.020	1.315	82.606	95.521
CC,CCT	62.663	642.630	402.690	1.604	82.174	97.125
TCC	14.274	407.510	58.170	0.232	81.254	97.357
TT,TTC	13.357	274.240	36.630	0.146	80.641	97.503
TTT,TTC	13.042	173.290	22.600	0.090	80.257	97.593
T,TTC	12.785	332.500	42.510	0.169	79.530	97.762
TTC	11.345	384.050	43.570	0.174	78.691	97.936
CCT	7.646	387.530	29.630	0.118	77.821	98.054
TCT	4.409	495.570	21.850	0.087	76.688	98.141
CTT	2.328	1359.690	31.650	0.126	73.668	98.267
TTT,TTT	0.200	217440.196	434.931	1.733	10.003	100.000

Circuit	Grade (%)	Recovery (%)
Rougher Only	77.799	97.369
Rougher Cleaner	81.298	95.867
Rougher Scavenger	75.872	97.688
Rougher Cleaner Scavenger	79.153	96.186



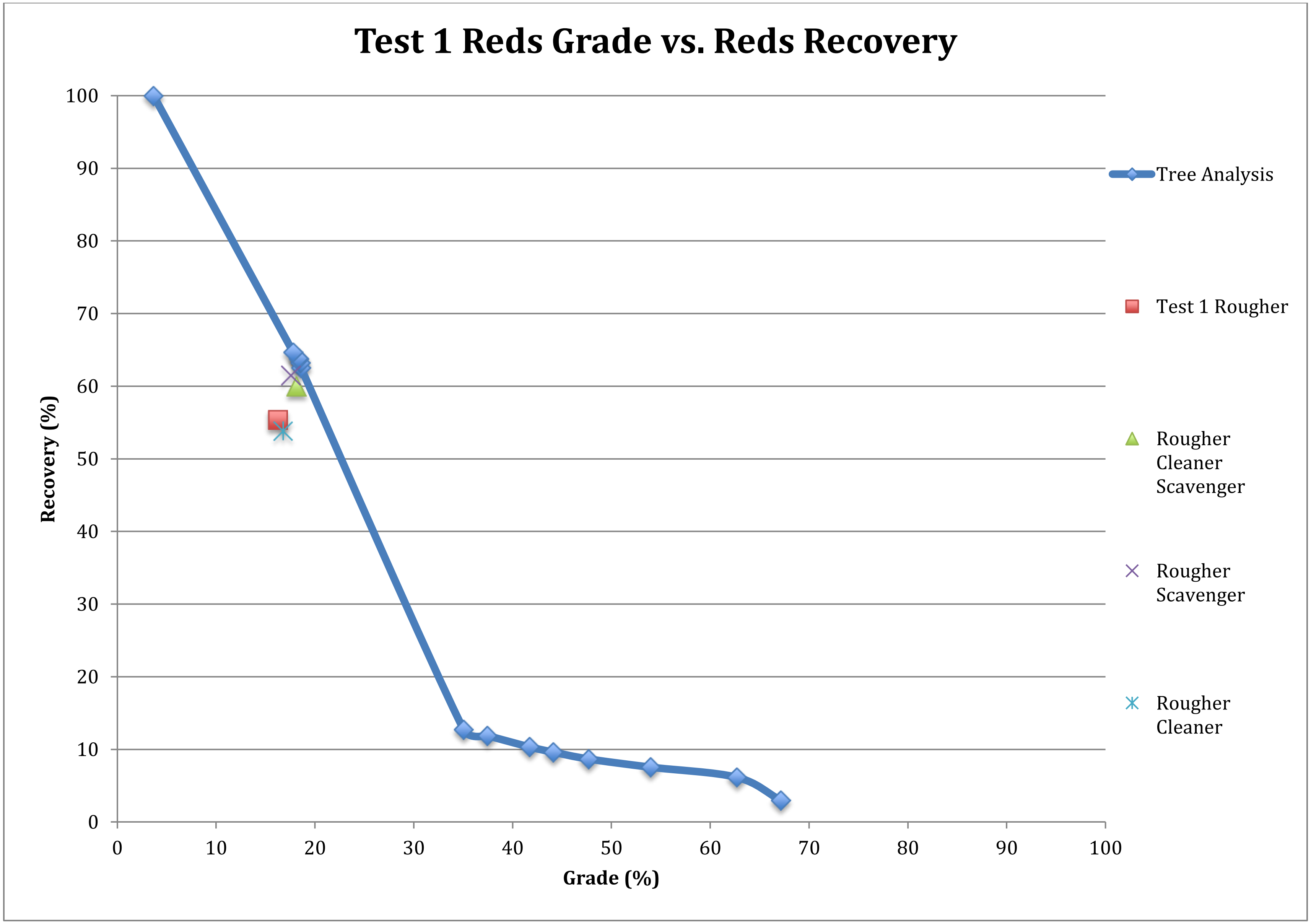
Test 1 Aluminum Grade vs. Aluminum Recovery
Aluminum Recovery (%)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
Aluminum Grade (%)
Tree Analysis
Test 1 Rougher
Rougher Cleaner Scavenger
Rougher Scavenger
Rougher Cleaner

Red Metals Grade and Recovery:

Sample	Reds Mass (g)	Fluff Mass (g)	Total Mass (g)	Reds Grade (%)
TTT,TTT	3256.805	213748.461	217440.196	1.498
TTT,TTC	10.210	140.480	173.290	5.892
TT,TTC	66.030	171.580	274.240	24.077
T,TTC	86.900	203.090	332.500	26.135
TTC	128.560	211.920	384.050	33.475
TCT	292.580	181.140	495.570	59.039
TCC	273.630	75.710	407.510	67.147
CTT	74.430	1253.610	1359.690	5.474
CTC	65.220	45.630	456.310	14.293
CCT	104.200	253.700	387.530	26.888
C,CCT	50.800	140.400	521.220	9.746
CC,CCT	143.100	96.840	642.630	22.268
CCC,CCT	77.780	42.520	422.470	18.411
CCC,CCC	4588.430	37.590	27624.042	16.610

Sample	Reds Grade (%)	Total Mass (g)	Reds Mass (g)	Reds Yield (%)	Cumulative Grade (%)	Cumulative Reds Mass (%)
TCC	67.147	407.510	273.630	2.968	67.147	2.968
TCT	59.039	495.570	292.580	3.174	62.698	6.142
TTC	33.475	384.050	128.560	1.395	53.978	7.537
CCT	26.888	387.530	104.200	1.130	47.709	8.667
T,TTC	26.135	332.500	86.900	0.943	44.135	9.610
TT,TTC	24.077	274.240	66.030	0.716	41.724	10.326
CC,CCT	22.268	642.630	143.100	1.552	37.448	11.878
CCC,CCT	18.411	422.470	77.780	0.844	35.045	12.722
CCC,CCC	16.610	27624.042	4588.430	49.773	18.602	62.495
CTC	14.293	456.310	65.220	0.707	18.540	63.202
C,CCT	9.746	521.220	50.800	0.551	18.396	63.754
TTT,TTC	5.892	173.290	10.210	0.111	18.329	63.864
CTT	5.474	1359.690	74.430	0.807	17.807	64.672
TTT,TTT	1.498	217440.196	3256.805	35.328	3.674	100.000

Circuit	Grade (%)	Recovery (%)
Rougher Only	16.247	55.365
Rougher Cleaner	16.773	53.851
Rougher Scavenger	17.545	61.507
Rougher Cleaner Scavenger	18.132	59.993



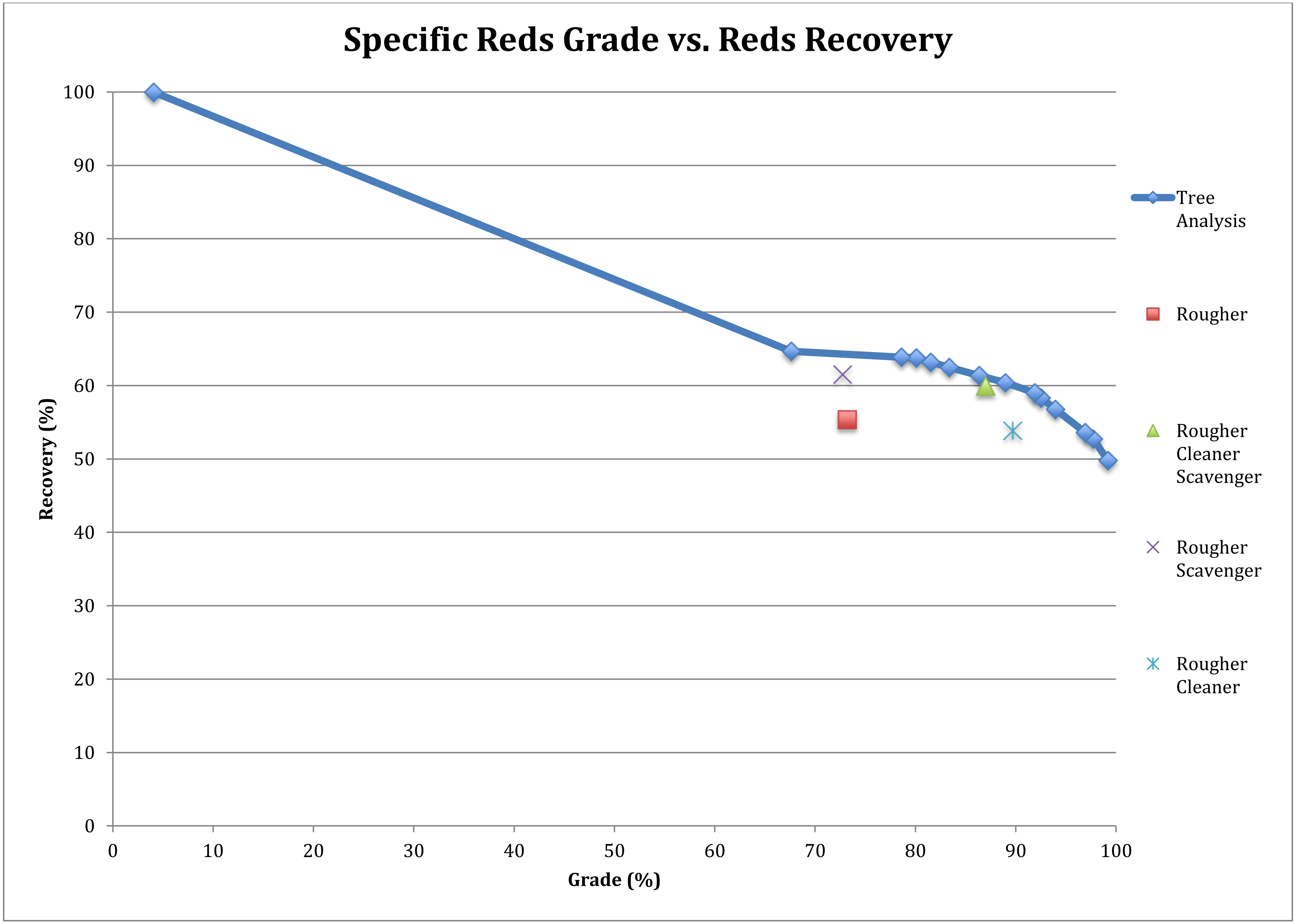
Test 1 Reds Grade vs. Reds Recovery
Recovery (%)
Grade (%)
0
10
20
30
40
50
60
70
80
90
100
Tree Analysis
Test 1 Rougher
Rougher Cleaner Scavenger
Rougher Scavenger
Rougher Cleaner

Specific Reds Grade vs. Recovery

Sample	Reds Mass (g)	Fluff Mass (g)	Total Relevant Mass (g)	Specific Reds Grade (%)
TTT,TTT	3256.805	213748.461	217005.265	1.501
TTT,TTC	10.210	140.480	150.690	6.775
TT,TTC	66.030	171.580	237.610	27.789
T,TTC	86.900	203.090	289.990	29.967
TTC	128.560	211.920	340.480	37.758
TCT	292.580	181.140	473.720	61.762
TCC	273.630	75.710	349.340	78.328
CTT	74.430	1253.610	1328.040	5.604
CTC	65.220	45.630	110.850	58.836
CCT	104.200	253.700	357.900	29.114
C,CCT	50.800	140.400	191.200	26.569
CC,CCT	143.100	96.840	239.940	59.640
CCC,CCT	77.780	42.520	120.300	64.655
CCC,CCC	4588.430	37.590	4626.020	99.187

Sample	Specific Reds Grade (%)	Total Relevant Mass (g)	Reds Mass (g)	Reds Yield (%)	Cumulative Specific Grade (%)	Cumulative Reds Mass (%)
CCC,CCC	99.187	4626.020	4588.430	49.773	99.187	49.773
TCC	78.328	349.340	273.630	2.968	97.723	52.741
CCC,CCT	64.655	120.300	77.780	0.844	96.942	53.585
TCT	61.762	473.720	292.580	3.174	93.950	56.759
CC,CCT	59.640	239.940	143.100	1.552	92.533	58.311
CTC	58.836	110.850	65.220	0.707	91.902	59.019
TTC	37.758	340.480	128.560	1.395	88.957	60.413
T,TTC	29.967	289.990	86.900	0.943	86.346	61.356
CCT	29.114	357.900	104.200	1.130	83.381	62.486
TT,TTC	27.789	237.610	66.030	0.716	81.532	63.202
C,CCT	26.569	191.200	50.800	0.551	80.100	63.754
TTT,TTC	6.775	150.690	10.210	0.111	78.625	63.864
CTT	5.604	1328.040	74.430	0.807	67.625	64.672
TTT,TTT	1.501	217005.265	3256.805	35.328	4.082	100.000

Circuit	Specific Grade (%)	Recovery (%)
Rougher Only	73.183	55.365
Rougher Cleaner	89.684	53.851
Rougher Scavenger	72.720	61.507
Rougher Cleaner Scavenger	86.979	59.993

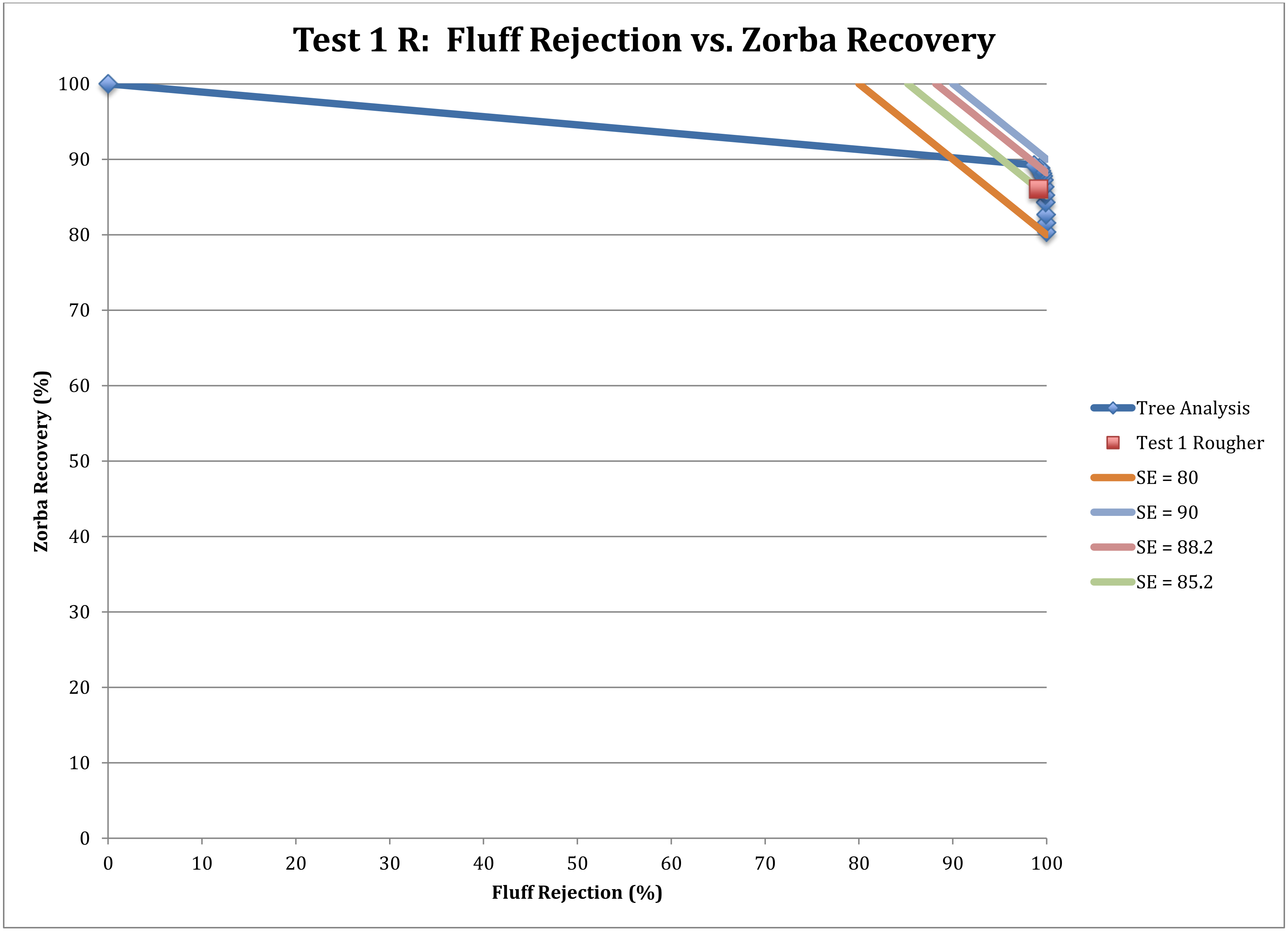

Specific Reds Grade vs. Reds Recovery
Recovery (%)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
Grade (%)
Tree Analysis
Rougher
Rougher Cleaner Scavenger
Rougher Scavenger
Rougher Cleaner

Zorba Recovery and Fluff Rejection:

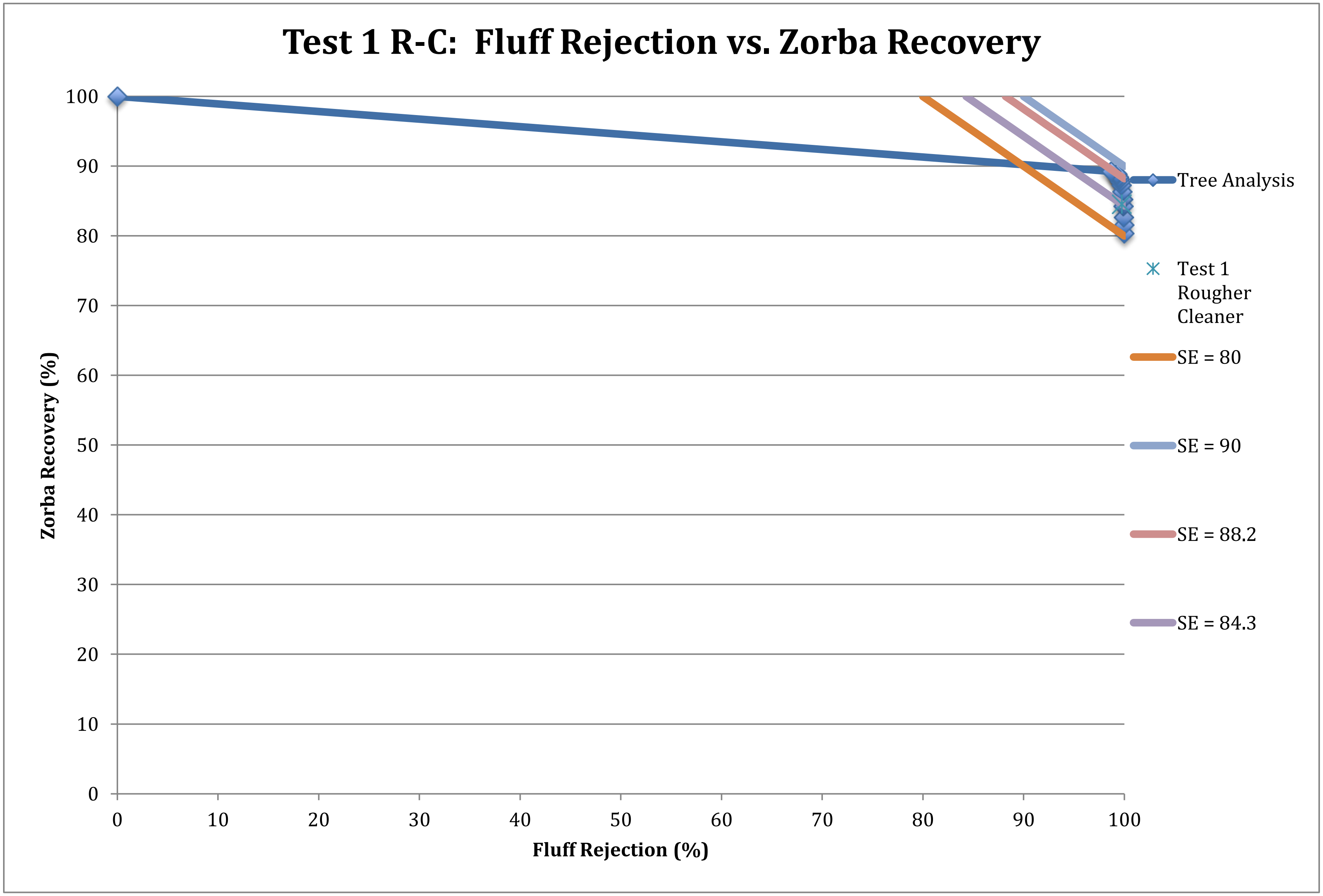
Sample	Zorba Mass (g)	Fluff Mass (g)	Total Mass (g)	Zorba Grade (%)
TTT,TTT	3691.736	213748.461	217440.196	1.698
TTT,TTC	32.810	140.480	173.290	18.934
TT,TTC	102.660	171.580	274.240	37.434
T,TTC	129.410	203.090	332.500	38.920
TTC	172.130	211.920	384.050	44.820
TCT	314.430	181.140	495.570	63.448
TCC	331.800	75.710	407.510	81.421
CTT	106.080	1253.610	1359.690	7.802
CTC	410.680	45.630	456.310	90.000
CCT	133.830	253.700	387.530	34.534
C,CCT	380.820	140.400	521.220	73.063
CC,CCT	545.790	96.840	642.630	84.931
CCC,CCT	379.950	42.520	422.470	89.935
CCC,CCC	27586.452	37.590	27624.042	99.864

Sample	Zorba Grade (%)	Fluff Yield (%)	Zorba Yield (%)	Cumulative Fluff Yield to T (%)	Cumulative Zorba Mass (%)	Separation Efficiency (%)
CCC,CCC	99.864	0.017	80.383	99.983	80.383	80.366
CTC	90.000	0.021	1.197	99.962	81.580	81.542
CCC,CCT	89.935	0.020	1.107	99.942	82.687	82.629
CC,CCT	84.931	0.045	1.590	99.897	84.278	84.175
TCC	81.421	0.035	0.967	99.862	85.244	85.107
C,CCT	73.063	0.065	1.110	99.797	86.354	86.152
TCT	63.448	0.084	0.916	99.714	87.270	86.984
TTC	44.820	0.098	0.502	99.616	87.772	87.388
T,TTC	38.920	0.094	0.377	99.522	88.149	87.671
TT,TTC	37.434	0.079	0.299	99.443	88.448	87.891
CCT	34.534	0.117	0.390	99.326	88.838	88.164
TTT,TTC	18.934	0.065	0.096	99.261	88.934	88.195
CTT	7.802	0.579	0.309	98.682	89.243	87.925
TTT,TTT	1.698	98.682	10.757	0.000	100.000	0.000

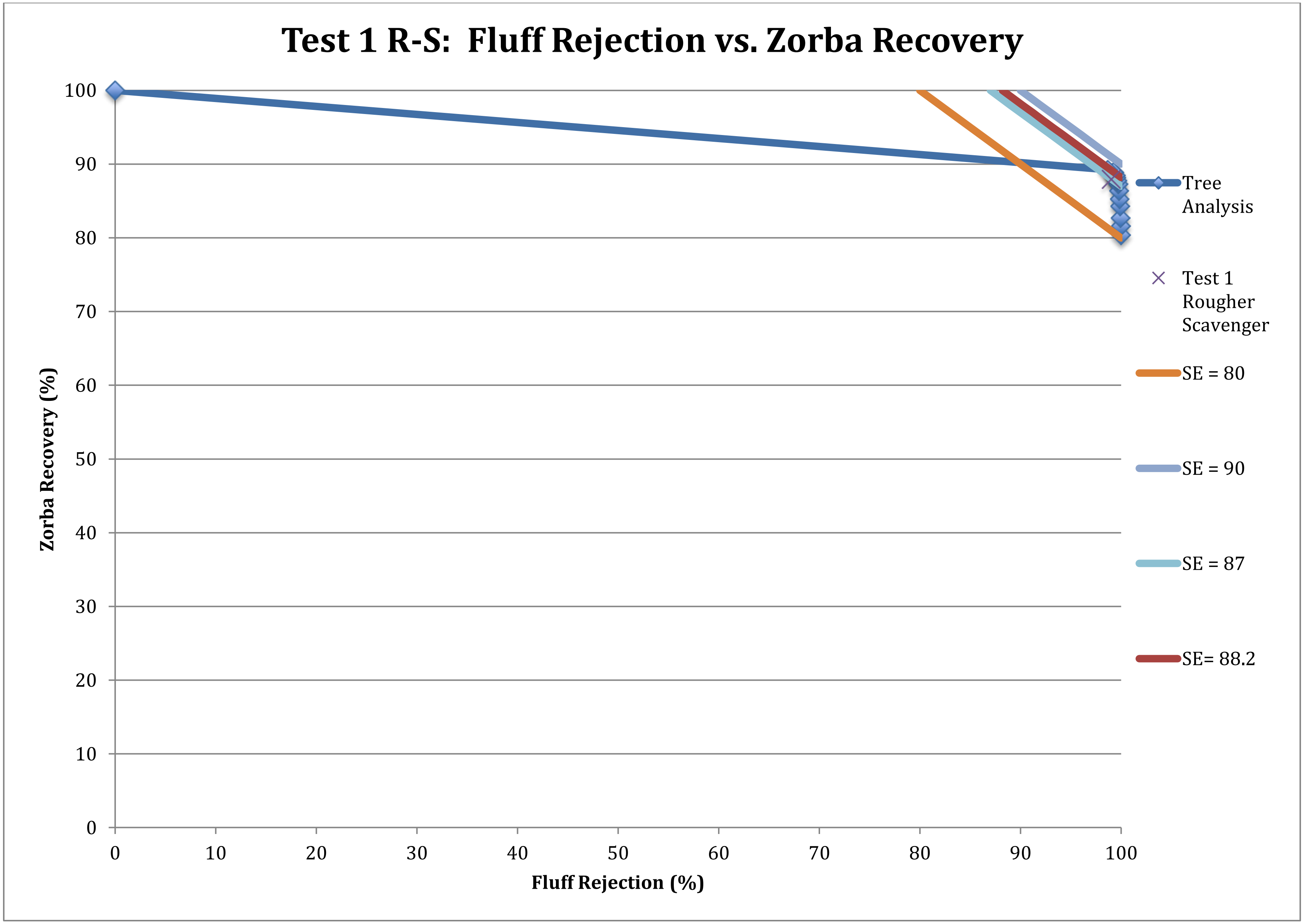
Circuit	Fluff Rejection (%)	Zorba Recovery (%)	Separation Efficiency (%)	Theoretical Efficiency (%)
Rougher Only	99.137	86.086	85.223	96.927
Rougher Cleaner	99.736	84.581	84.317	95.896
Rougher Scavenger	99.018	87.969	86.987	98.933
Rougher Cleaner Scavenger	99.618	86.464	86.081	97.903

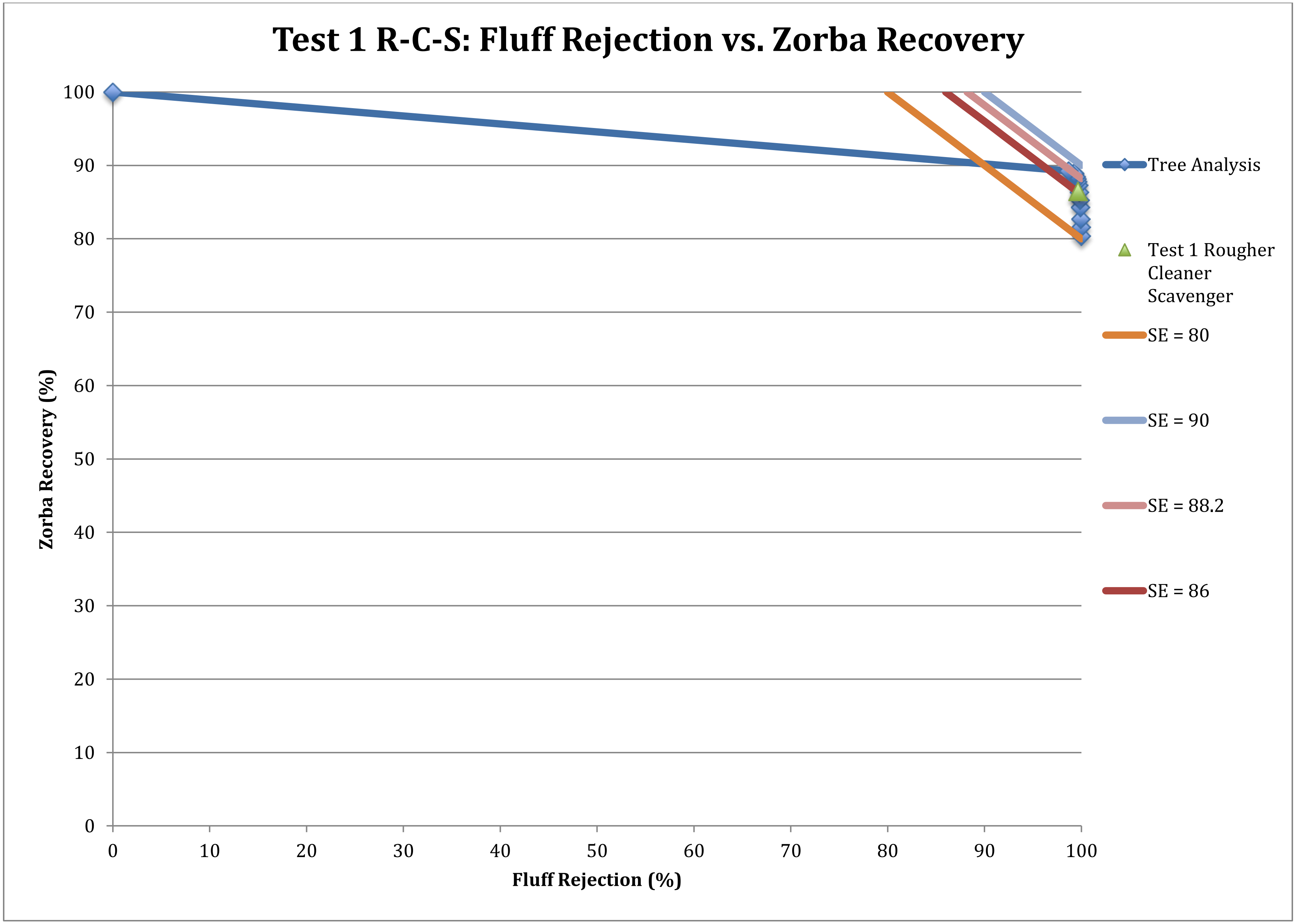


Test 1 R: Fluff Rejection vs. Zorba Recovery
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
Zorba Recovery (%)
Fluff Rejection (%)
Tree Analysis
Test 1 Rougher
SE = 80
SE = 90
SE = 88.2
SE = 85.2



Test 1 R-C: Fluff Rejection vs. Zorba Recovery
100
90
80
70
60
50
40
30
20
10
0
Zorba Recovery (%)
0
10
20
30
40
50
60
70
80
90
100
Fluff Rejection (%)
Tree Analysis
Test 1 Rougher Cleaner
SE = 80
SE = 90
SE = 88.2
SE = 84.3


Test 1 R-S: Fluff Rejection vs. Zorba Recovery
Zorba Recovery (%)
Fluff Rejection (%)
0
10
20
30
40
50
60
70
80
90
100
Tree Analysis
Test 1 Rougher Scavenger
SE = 80
SE = 90
SE = 87
SE= 88.2

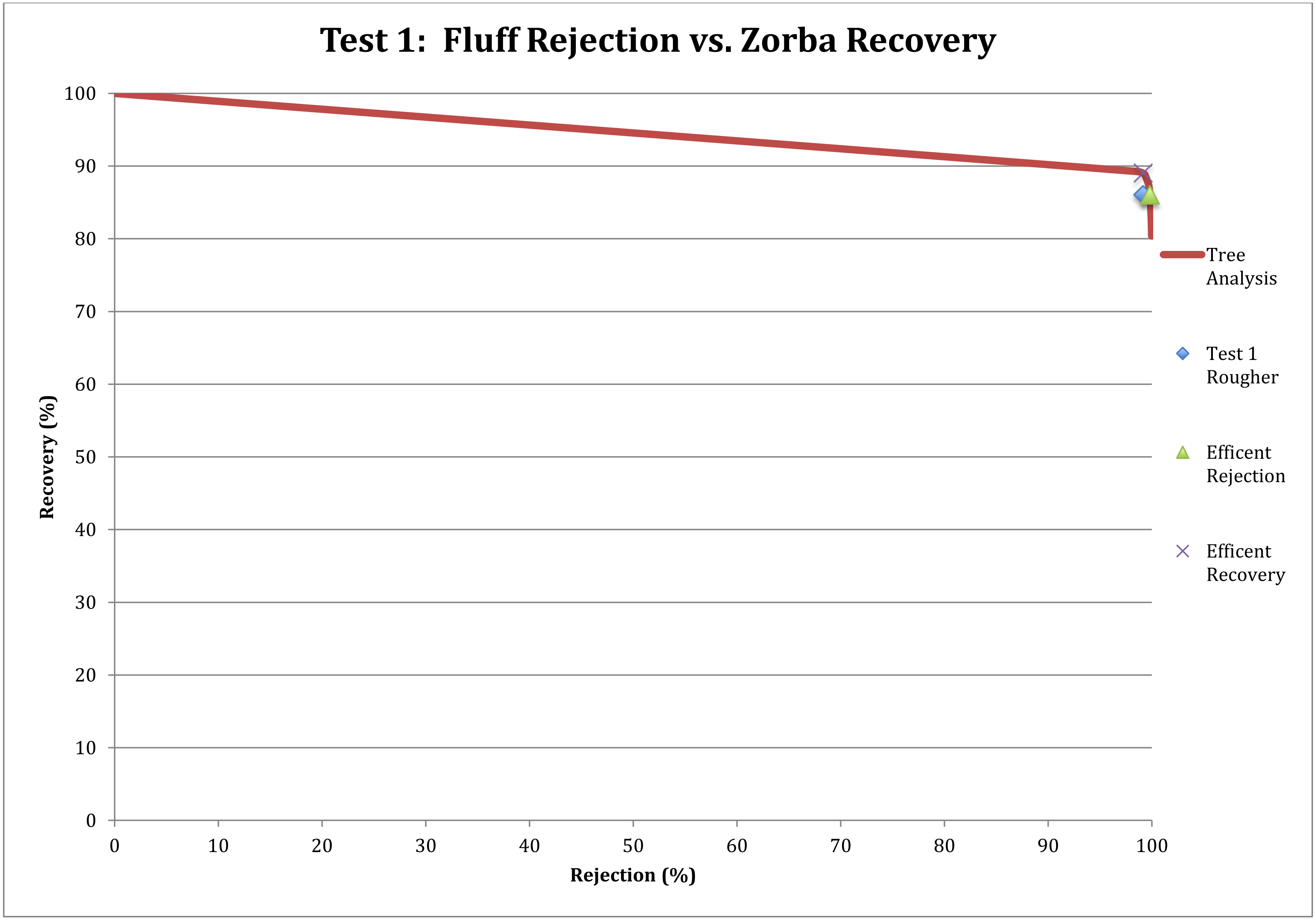

Test 1 R-C-S: Fluff Rejection vs. Zorba Recovery
Zorba Recovery (%)
Fluff Rejection (%)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
Tree Analysis
Test 1 Rougher Cleaner Scavenger
SE = 80
SE = 90
SE = 88.2
SE = 86

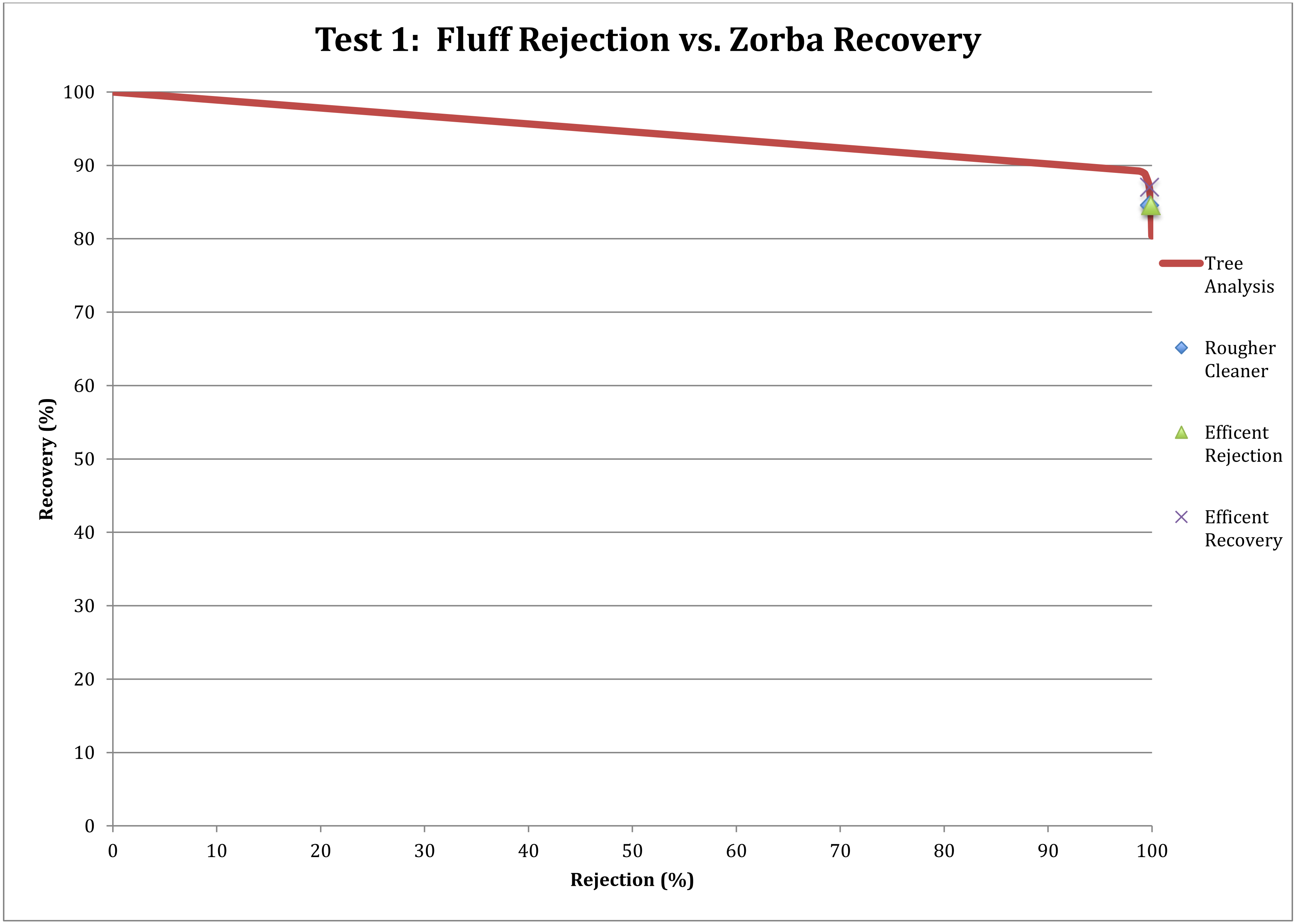
Rejection Efficiency, Recovery Efficiency, and Spline Fitting

Sample	Fluff Rejection (x)	Cumulative Zorba Mass (y)	s	dy	dx	m
CCC,CCC	99.983	80.383	-56.8051	1.1967	-0.0211	
CTC	99.962	81.580	-56.3985	1.1071	-0.0196	-56.6018
CCC,CCT	99.942	82.687	-35.5718	1.5904	-0.0447	-45.9851
CC,CCT	99.897	84.278	-27.6603	0.9668	-0.0350	-31.6161
TCC	99.862	85.244	-17.1193	1.1097	-0.0648	-22.3898
C,CCT	99.797	86.354	-10.9558	0.9162	-0.0836	-14.0376
TCT	99.714	87.270	-5.1265	0.5016	-0.0978	-8.0411
TTC	99.616	87.772	-4.0217	0.3771	-0.0938	-4.5741
T,TTC	99.522	88.149	-3.7763	0.2991	-0.0792	-3.8990
TT,TTC	99.443	88.448	-3.3294	0.3900	-0.1171	-3.5529
CCT	99.326	88.838	-1.4741	0.0956	-0.0649	-2.4018
TTT,TTC	99.261	88.934	-0.5341	0.3091	-0.5788	-1.0041
CTT	98.682	89.243	-0.1090	10.7573	-98.6723	-0.3215
TTT,TTT	0.010	100.000	0.0000	0.0000	-0.0090	-0.0545

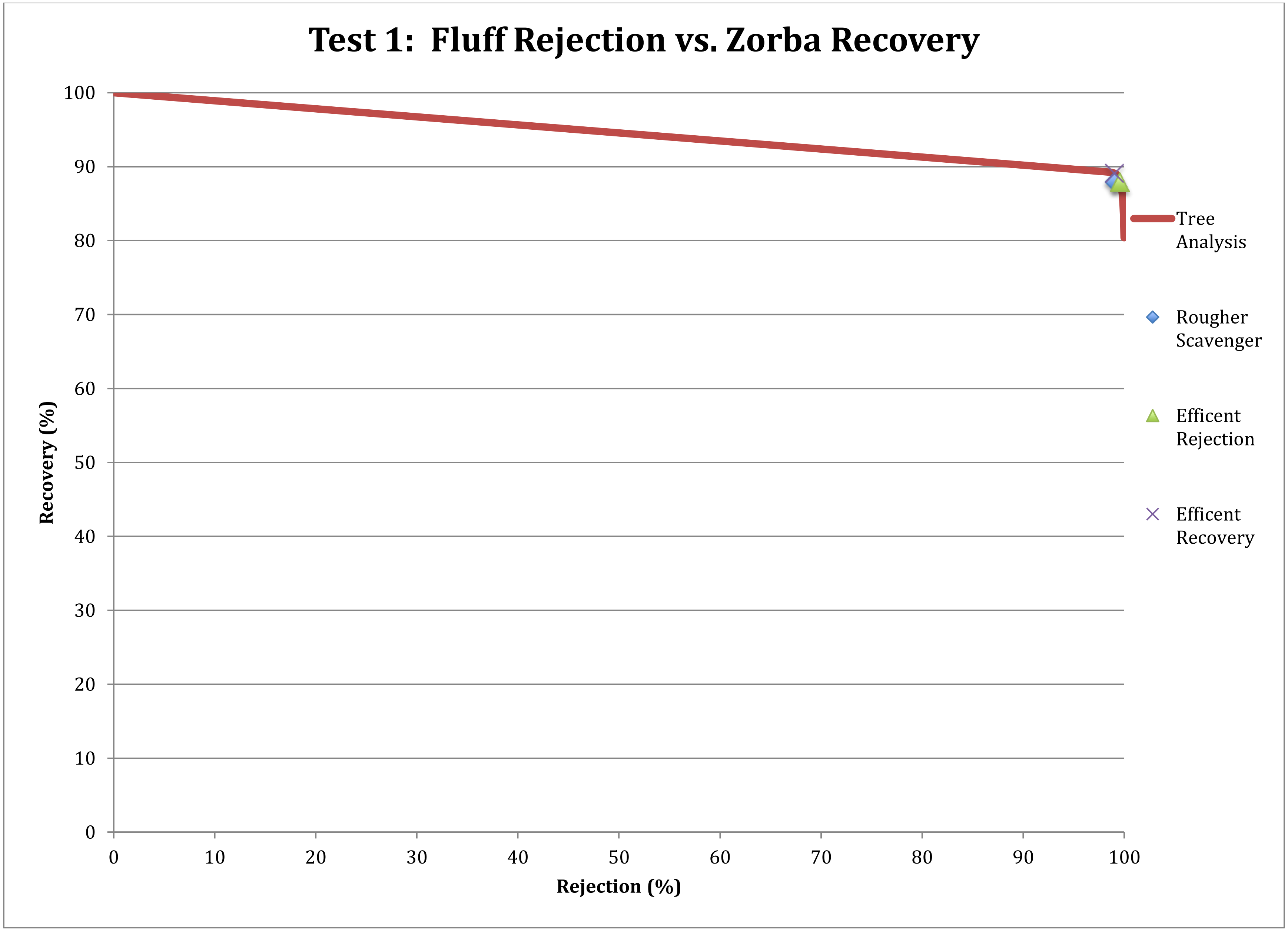
Sample	a	b	c	d
CCC,CCC	80.3834	0.0000	5402.6575	128459.3964
CTC	81.5801	-56.6018	509.7583	26495.3719
CCC,CCT	82.6872	-45.9851	-377.3561	-3230.6839
CC,CCT	84.2776	-31.6161	-75.5551	1076.1681
TCC	85.2444	-22.3898	-115.0776	-520.9373
C,CCT	86.3541	-14.0376	-38.8493	-23.8949
TCT	87.2703	-8.0411	-53.9355	-246.7841
TTC	87.7719	-4.5741	-10.4737	-48.8740
T,TTC	88.1489	-3.8990	-0.2772	16.0557
TT,TTC	88.4481	-3.5529	4.1045	51.3315
CCT	88.8380	-2.4018	-21.3597	-108.8003
TTT,TTC	88.9336	-1.0041	-1.2570	-0.7687
CTT	89.2427	-0.3215	-0.0038	0.0000
TTT,TTT	100.0000	-0.0545	5555543.4422	617283277.6544

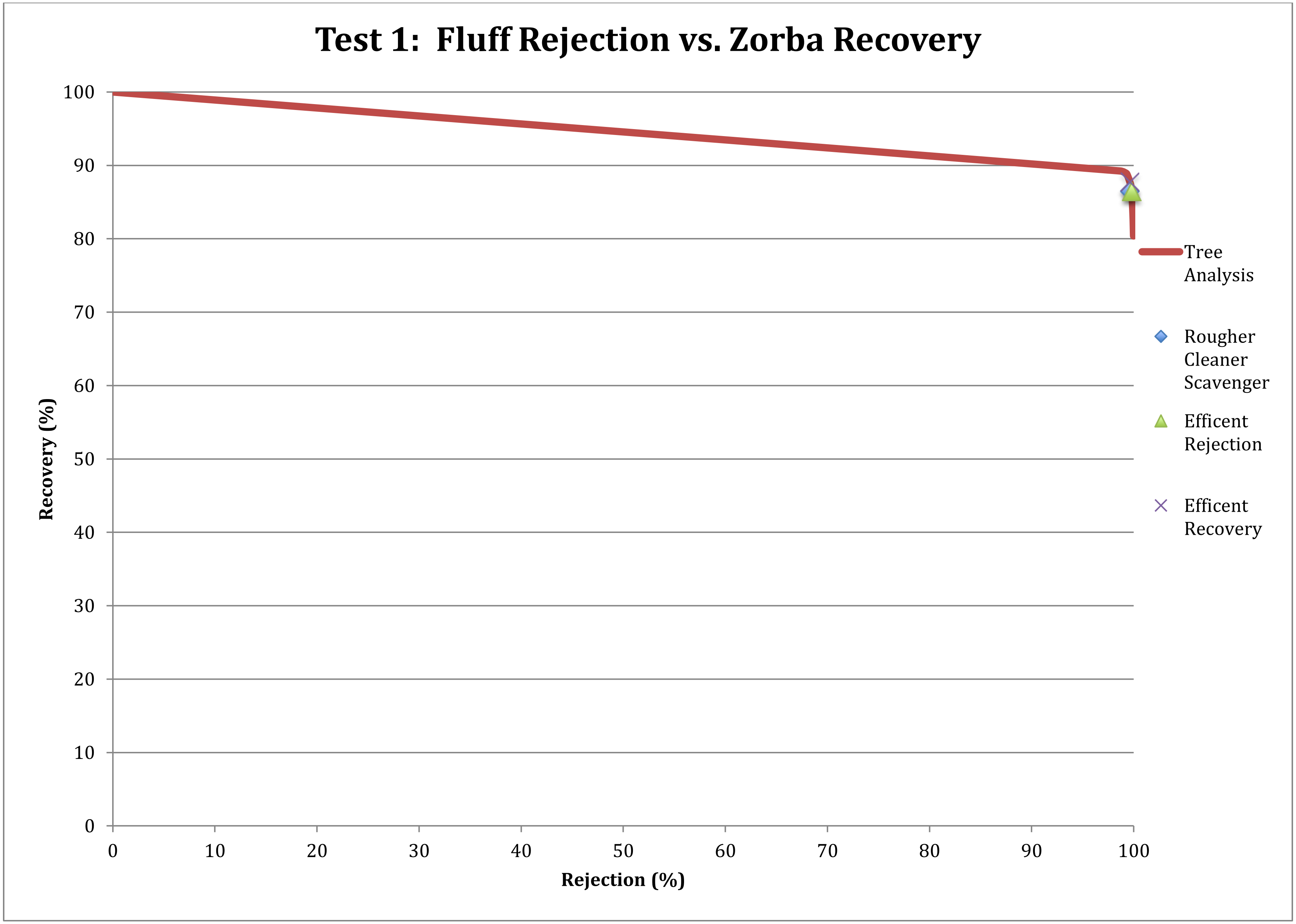
Test	Fluff Rejection (%)	Zorba Recovery (%)	Efficient Rejection (%)	Efficient Recovery (%)	Rejection Efficiency (%)	Recovery Efficiency
Rougher	99.137	86.086	99.816	89.068	99.319	96.652
Rougher Cleaner	99.736	84.581	99.888	87.066	99.849	95.577
Rougher Scavenger	99.018	87.969	99.569	89.124	99.447	98.704
Rougher Cleaner Scavenger	99.618	86.464	99.784	87.764	99.834	97.523


Test 1: Fluff Rejection vs. Zorba Recovery
100
90
80
70
60
50
40
30
20
10
0
Recovery (%)
0
10
20
30
40
50
60
70
80
90
100
Rejection (%)
Tree Analysis
Test 1 Rougher
Efficent Rejection
Efficent Recovery



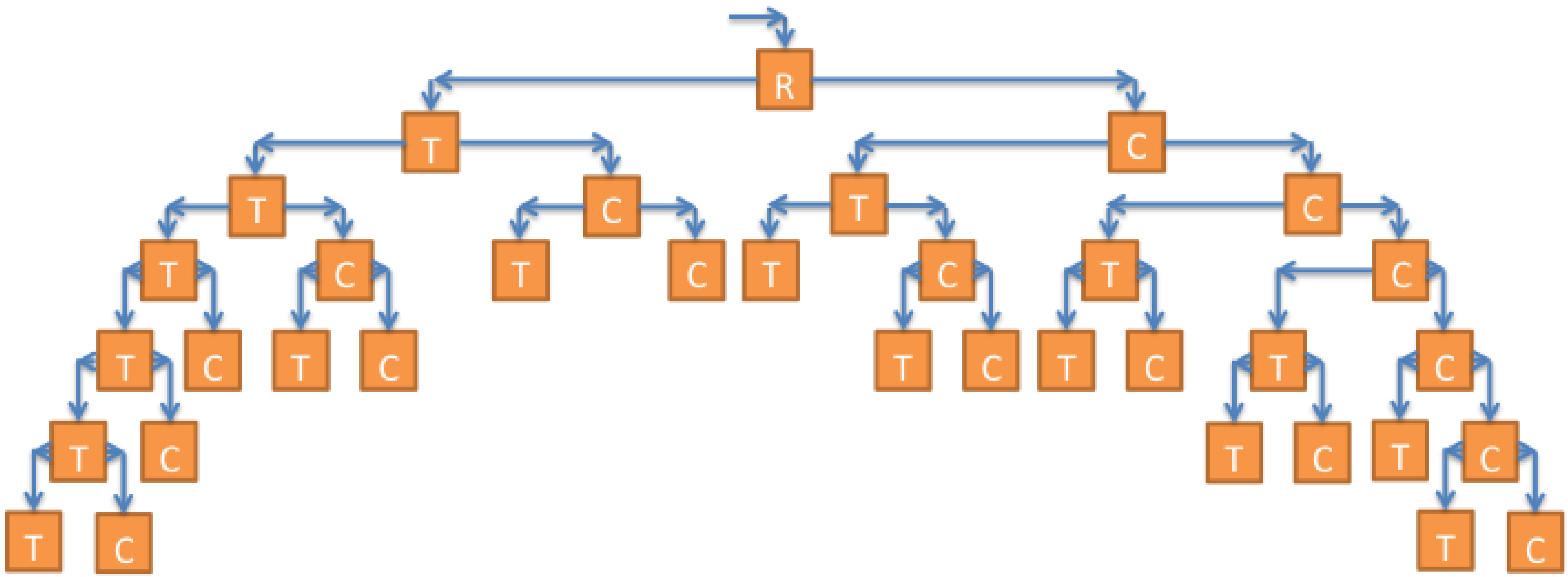
Test 1: Fluff Rejection vs. Zorba Recovery
Recovery (%)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
Rejection (%)
Tree Analysis
Rougher Cleaner
Efficent Rejection
Efficent Recovery


Test 1: Fluff Rejection vs. Zorba Recovery
Recovery (%)
Rejection (%)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
Tree Analysis
Rougher Scavenger
Efficent Rejection
Efficent Recovery


Test 1: Fluff Rejection vs. Zorba Recovery
Recovery (%)
Rejection (%)
0
10
20
30
40
50
60
70
80
90
100
Tree Analysis
Rougher Cleaner Scavenger
Efficent Rejection
Efficent Recovery

APPENDIX D: TREE ANALYSIS FOR TEST 2

Tree Sample Diagram:

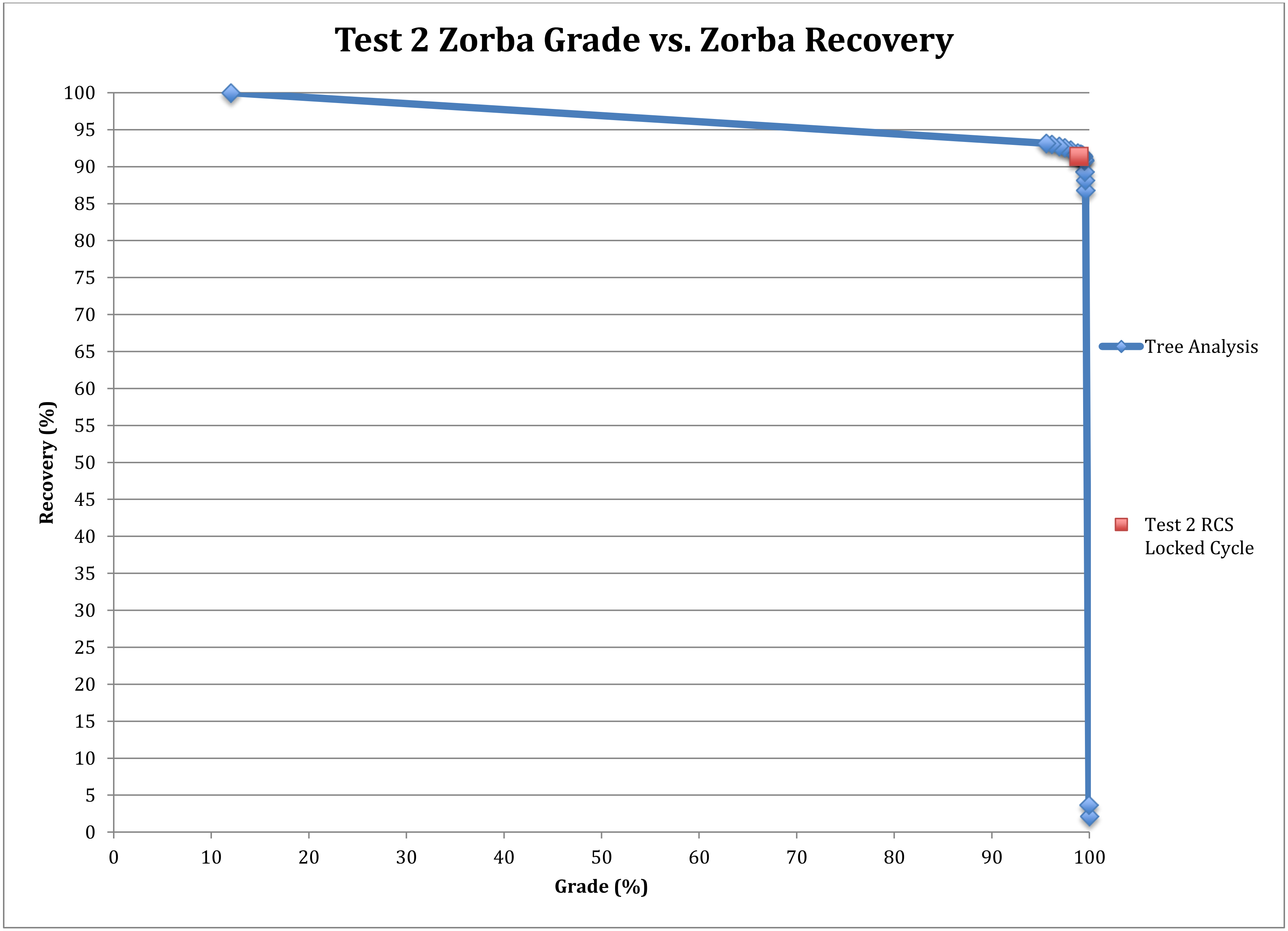


Zorba Grade and Recovery:

Sample	Reds Mass (g)	Fluff Mass (g)	Zorba Metals (g)	Total Mass (g)
TTT,TTT	1570.11	218839.56	2059.75	220899.30
TTT,TTC	20.72	173.90	43.32	217.22
TT,TTC	27.27	164.42	63.90	228.32
T,TTC	48.03	181.50	90.54	272.04
T,TCT	26.48	234.54	70.05	304.59
T,TCC	21.22	10.71	43.07	53.78
TCT	57.72	211.76	115.89	327.65
TCC	55.00	23.85	110.10	133.95
CTT	17.64	82.26	51.87	134.13
C,TCT	17.21	6.68	37.41	44.09
C,TCC	125.02	0.00	631.95	631.95
C,CTT	8.50	47.99	40.15	88.14
C,CTC	119.87	0.52	465.33	465.85
CC,CTT	8.16	16.05	37.79	53.84
CC,CTC	83.23	7.21	413.25	420.46
CC,CCT	58.23	18.58	460.92	479.50
CCC,CCT	37.79	13.40	339.96	353.36
CCC,CCC	2891.20	102.51	25029.66	25132.17

Sample	Zorba Grade (%)	Total Mass (g)	Zorba Mass (g)	Zorba Yield (%)	Cumulative Grade (%)	Cumulative Zorba Mass (%)
C,TCC	100.000	631.950	631.950	2.099	100.000	2.099
C,CTC	99.888	465.850	465.330	1.546	99.953	3.645
CCC,CCC	99.592	25132.172	25029.660	83.141	99.607	86.786
CC,CTC	98.285	420.460	413.250	1.373	99.586	88.159
CCC,CCT	96.208	353.360	339.960	1.129	99.542	89.288
CC,CCT	96.125	479.500	460.920	1.531	99.483	90.819
C,TCT	84.849	44.090	37.410	0.124	99.459	90.944
TCC	82.195	133.950	110.100	0.366	99.375	91.309
T,TCC	80.086	53.780	43.070	0.143	99.338	91.452
CC,CTT	70.189	53.840	37.790	0.126	99.282	91.578
C,CTT	45.553	88.140	40.150	0.133	99.112	91.711
CTT	38.671	134.130	51.870	0.172	98.822	91.884
TCT	35.370	327.650	115.890	0.385	98.088	92.269
T,TTC	33.282	272.040	90.540	0.301	97.471	92.569
TT,TTC	27.987	228.320	63.900	0.212	96.921	92.782
T,TCT	22.998	304.590	70.050	0.233	96.148	93.014
TTT,TTC	19.943	217.220	43.320	0.144	95.583	93.158
TTT,TTT	0.932	220899.304	2059.745	6.842	12.030	100.000

Circuit	Grade (%)	Recovery (%)
RCS Locked Cycle	98.938	91.375

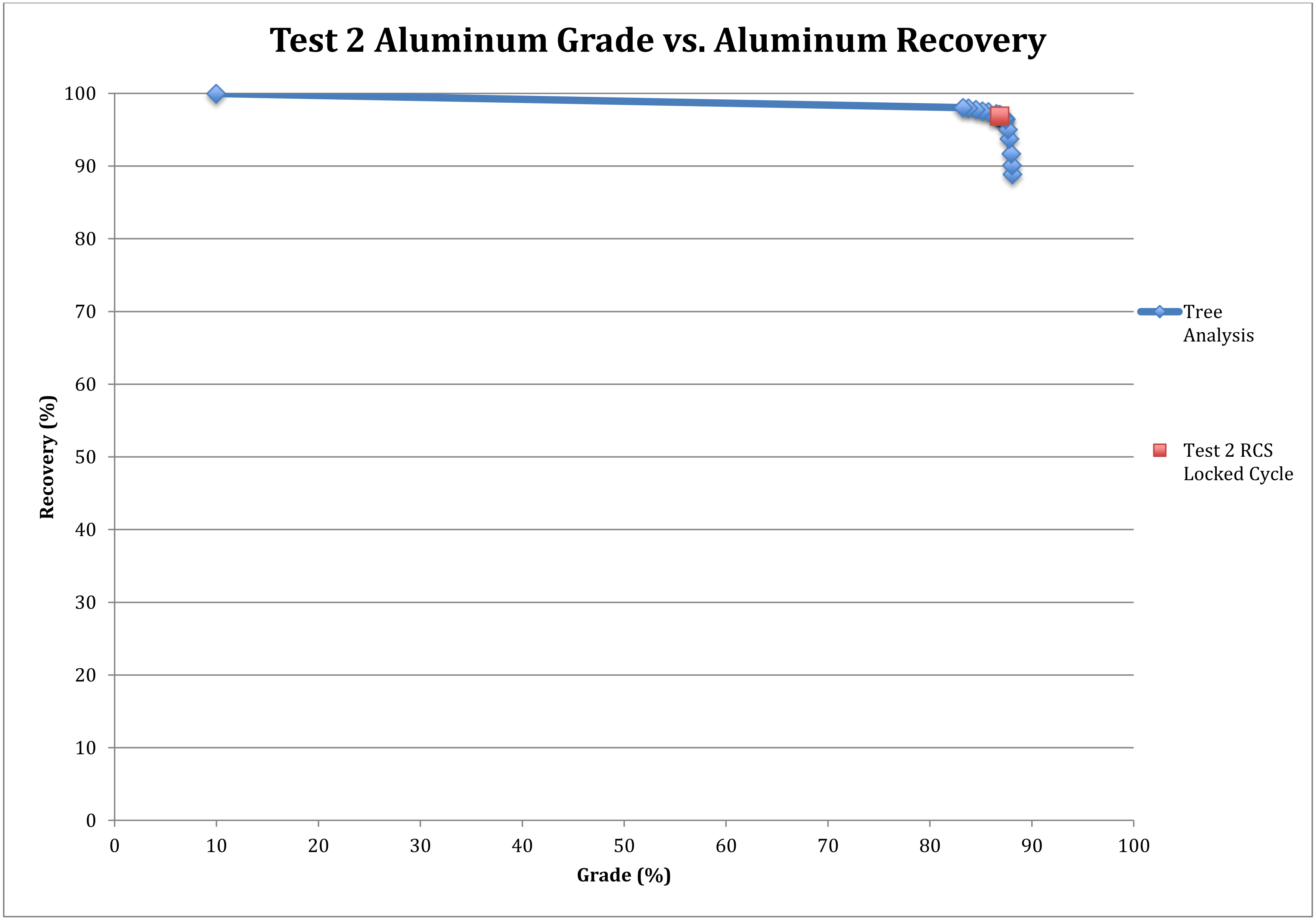

Test 2 Zorba Grade vs. Zorba Recovery
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
Recovery (%)
0
10
20
30
40
50
60
70
80
90
100
Grade (%)
Tree Analysis
Test 2 RCS Locked Cycle

Aluminum Grade and Recovery:

Sample	Al Mass (g)	Fluff Mass (g)	Total Mass (g)	Aluminum Grade (%)
TTT,TTT	489.638	218839.559	220899.304	0.222
TTT,TTC	22.600	173.900	217.220	10.404
TT,TTC	36.630	164.420	228.320	16.043
T,TTC	42.510	181.500	272.040	15.626
T,TCT	43.570	234.540	304.590	14.304
T,TCC	21.850	10.710	53.780	40.628
TCT	58.170	211.760	327.650	17.754
TCC	55.100	23.850	133.950	41.135
CTT	34.230	82.260	134.130	25.520
C,TCT	20.200	6.680	44.090	45.815
C,TCC	506.930	0.000	631.950	80.217
C,CTT	31.650	47.990	88.140	35.909
C,CTC	345.460	0.520	465.850	74.157
CC,CTT	29.630	16.050	53.840	55.033
CC,CTC	330.020	7.210	420.460	78.490
CC,CCT	402.690	18.580	479.500	83.981
CCC,CCT	302.170	13.400	353.360	85.513
CCC,CCC	22138.465	102.512	25132.172	88.088

Sample	Al Grade (%)	Total Mass (g)	Al Mass (g)	Al Yield (%)	Cumulative Grade (%)	Cumulative Al Mass (%)
CCC,CCC	88.088	25132.172	22138.465	88.868	88.088	88.868
CCC,CCT	85.513	353.360	302.170	1.213	88.052	90.081
CC,CCT	83.981	479.500	402.690	1.616	87.977	91.698
C,TCC	80.217	631.950	506.930	2.035	87.793	93.733
CC,CTC	78.490	420.460	330.020	1.325	87.648	95.058
C,CTC	74.157	465.850	345.460	1.387	87.419	96.444
CC,CTT	55.033	53.840	29.630	0.119	87.356	96.563
C,TCT	45.815	44.090	20.200	0.081	87.290	96.644
TCC	41.135	133.950	55.100	0.221	87.067	96.866
T,TCC	40.628	53.780	21.850	0.088	86.977	96.953
C,CTT	35.909	88.140	31.650	0.127	86.815	97.080
CTT	25.520	134.130	34.230	0.137	86.521	97.218
TCT	17.754	327.650	58.170	0.234	85.726	97.451
TT,TTC	16.043	228.320	36.630	0.147	85.168	97.598
T,TTC	15.626	272.040	42.510	0.171	84.512	97.769
T,TCT	14.304	304.590	43.570	0.175	83.778	97.944
TTT,TTC	10.404	217.220	22.600	0.091	83.235	98.034
TTT,TTT	0.222	220899.304	489.638	1.966	9.955	100.000

Circuit	Al Grade (%)	Recovery (%)
RCS Locked Cycle	86.829	96.909



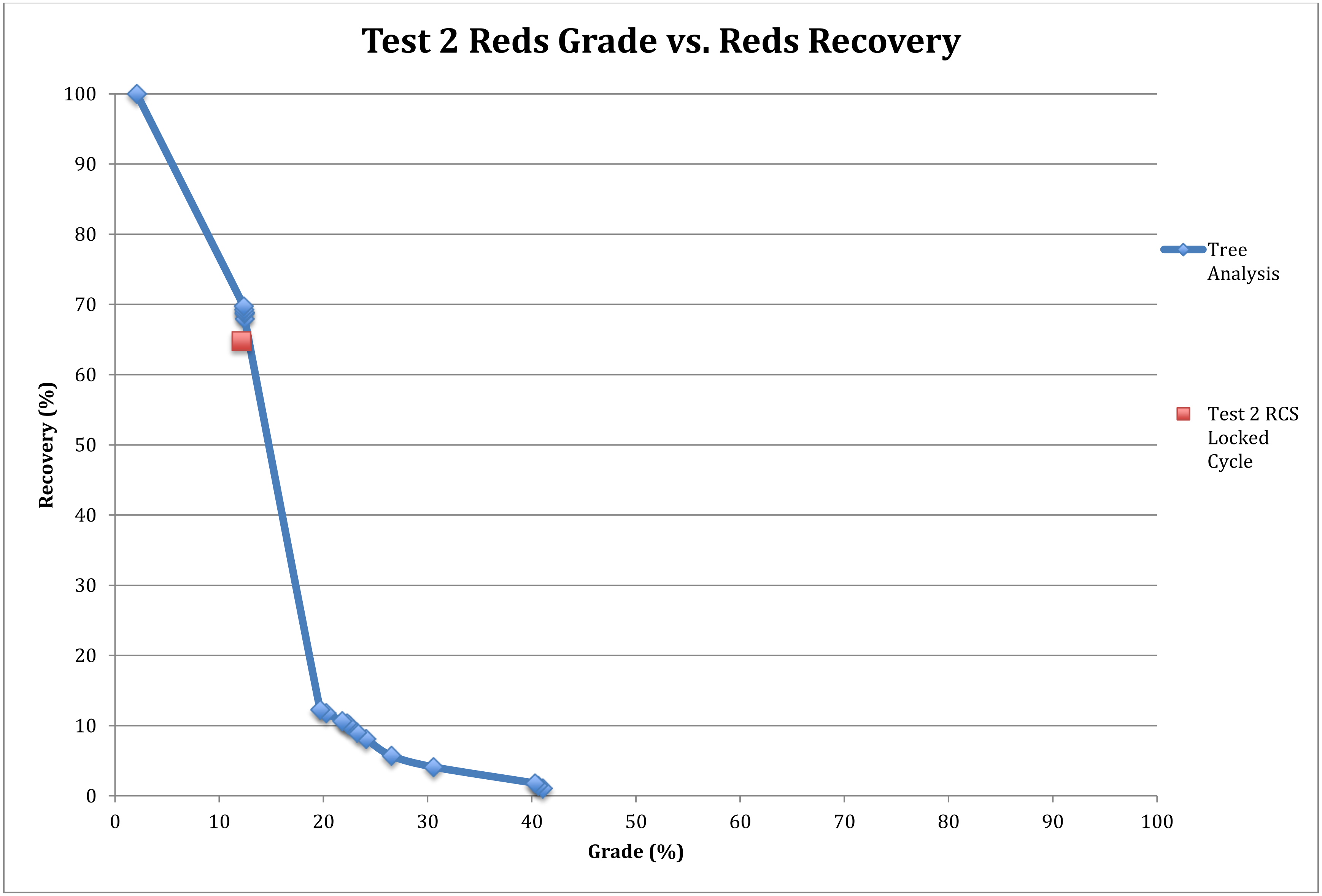
Test 2 Aluminum Grade vs. Aluminum Recovery
Recovery (%)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
Grade (%)
Tree Analysis
Test 2 RCS Locked Cycle

Red Metals Grade and Recovery:

Sample	Reds Mass (g)	Fluff Mass (g)	Total Mass (g)	Reds Grade (%)
TTT,TTT	1570.107	218839.559	220899.304	0.711
TTT,TTC	20.720	173.900	217.220	9.539
TT,TTC	27.270	164.420	228.320	11.944
T,TTC	48.030	181.500	272.040	17.655
T,TCT	26.480	234.540	304.590	8.694
T,TCC	21.220	10.710	53.780	39.457
TCT	57.720	211.760	327.650	17.616
TCC	55.000	23.850	133.950	41.060
CTT	17.640	82.260	134.130	13.151
C,TCT	17.210	6.680	44.090	39.034
C,TCC	125.020	0.000	631.950	19.783
C,CTT	8.500	47.990	88.140	9.644
C,CTC	119.870	0.520	465.850	25.731
CC,CTT	8.160	16.050	53.840	15.156
CC,CTC	83.230	7.210	420.460	19.795
CC,CCT	58.230	18.580	479.500	12.144
CCC,CCT	37.790	13.400	353.360	10.694
CCC,CCC	2891.195	102.512	25132.172	11.504

Sample	Reds Grade (%)	Total Mass (g)	Reds Mass (g)	Reds Yield (%)	Cumulative Grade (%)	Cumulative Reds Mass (%)
TCC	41.060	133.950	55.000	1.059	41.060	1.059
T,TCC	39.457	53.780	21.220	0.409	40.601	1.468
C,TCT	39.034	44.090	17.210	0.331	40.303	1.799
C,CTC	25.731	465.850	119.870	2.308	30.573	4.107
CC,CTC	19.795	420.460	83.230	1.603	26.520	5.710
C,TCC	19.783	631.950	125.020	2.407	24.087	8.117
T,TTC	17.655	272.040	48.030	0.925	23.222	9.042
TCT	17.616	327.650	57.720	1.111	22.440	10.153
CC,CTT	15.156	53.840	8.160	0.157	22.277	10.310
CTT	13.151	134.130	17.640	0.340	21.795	10.650
CC,CCT	12.144	479.500	58.230	1.121	20.261	11.771
TT,TTC	11.944	228.320	27.270	0.525	19.676	12.296
CCC,CCC	11.504	25132.172	2891.195	55.671	12.439	67.967
CCC,CCT	10.694	353.360	37.790	0.728	12.417	68.695
C,CTT	9.644	88.140	8.500	0.164	12.409	68.858
TTT,TTC	9.539	217.220	20.720	0.399	12.387	69.257
T,TCT	8.694	304.590	26.480	0.510	12.349	69.767
TTT,TTT	0.711	220899.304	1570.107	30.233	2.075	100.000

Circuit	Grade (%)	Recovery (%)
RCS Locked Cycle	12.109	64.829



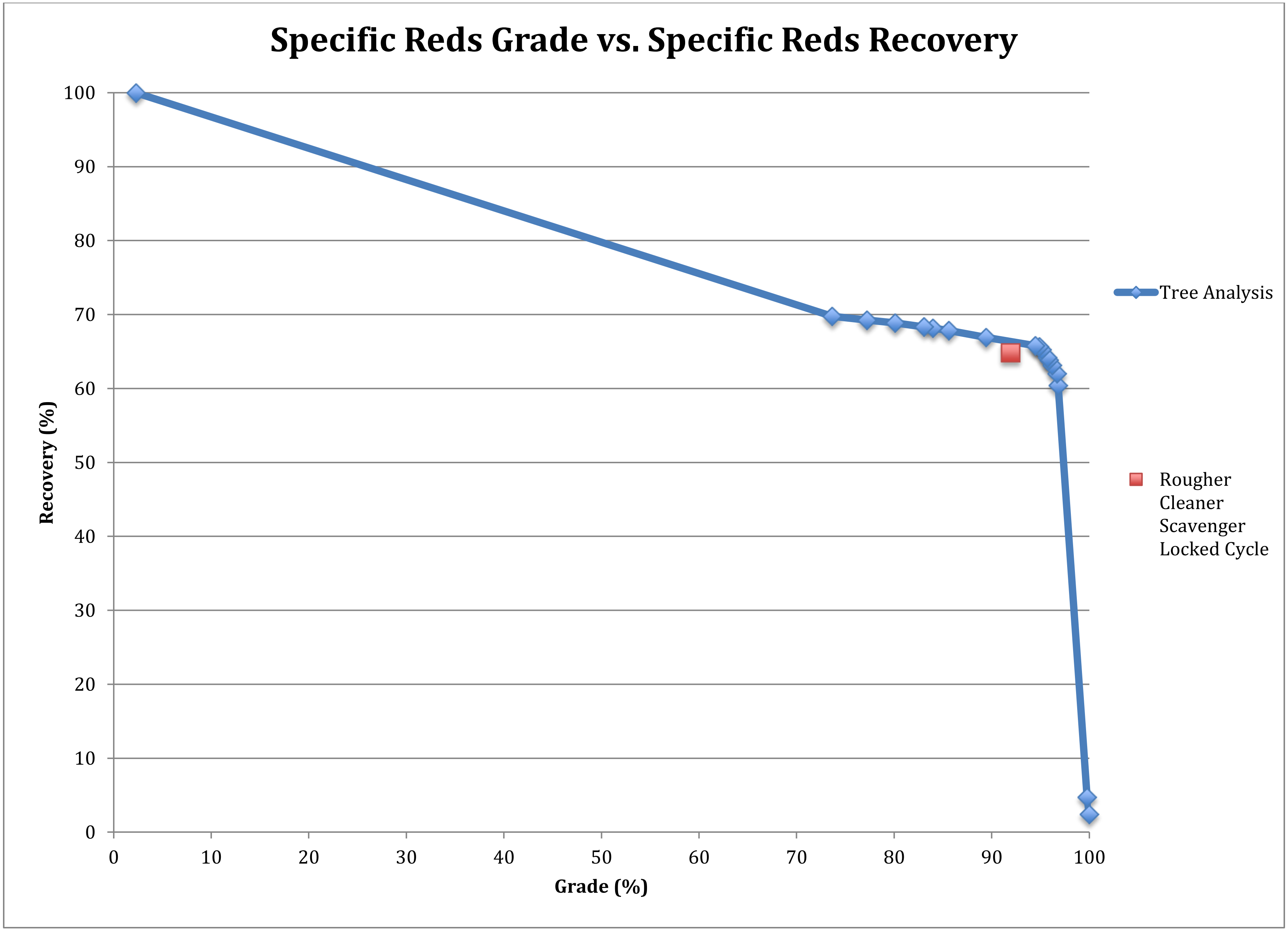
Test 2 Reds Grade vs. Reds Recovery
Recovery (%)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
Grade (%)
Tree Analysis
Test 2 RCS Locked Cycle

Specific Reds Grade and Recovery:

Sample	Reds Mass (g)	Fluff Mass (g)	Total Relevant Mass (g)	Specific Reds Grade (%)
TTT,TTT	1570.107	218839.559	220409.666	0.712
TTT,TTC	20.720	173.900	194.620	10.646
TT,TTC	27.270	164.420	191.690	14.226
T,TTC	48.030	181.500	229.530	20.925
T,TCT	26.480	234.540	261.020	10.145
T,TCC	21.220	10.710	31.930	66.458
TCT	57.720	211.760	269.480	21.419
TCC	55.000	23.850	78.850	69.753
CTT	17.640	82.260	99.900	17.658
CTCT	17.210	6.680	23.890	72.039
CTCC	125.020	0.000	125.020	100.000
CCTT	8.500	47.990	56.490	15.047
CCTC	119.870	0.520	120.390	99.568
CC,CTT	8.160	16.050	24.210	33.705
CC,CTC	83.230	7.210	90.440	92.028
CC,CCT	58.230	18.580	76.810	75.810
CCC,CCT	37.790	13.400	51.190	73.823
CCC,CCC	2891.195	102.512	2993.707	96.576

Sample	Specific Reds Grade (%)	Total Relevant Mass (g)	Reds Mass (g)	Reds Yield (%)	Cumulative Specific Grade (%)	Cumulative Reds Mass (%)
CTCC	100.000	125.020	125.020	2.407	100.000	2.099
CCTC	99.568	120.390	119.870	2.308	99.788	3.645
CCC,CCC	96.576	2993.707	2891.195	55.671	96.819	86.786
CC,CTC	92.028	90.440	83.230	1.603	96.689	88.159
CC,CCT	75.810	76.810	58.230	1.121	96.218	89.288
CCC,CCT	73.823	51.190	37.790	0.728	95.887	90.819
CTCT	72.039	23.890	17.210	0.331	95.723	90.944
TCC	69.753	78.850	55.000	1.059	95.148	91.309
T,TCC	66.458	31.930	21.220	0.409	94.893	91.452
CC,CTT	33.705	24.210	8.160	0.157	94.483	91.578
TCT	21.419	269.480	57.720	1.111	89.416	91.711
T,TTC	20.925	229.530	48.030	0.925	85.596	91.884
CTT	17.658	99.900	17.640	0.340	83.986	92.269
CCTT	15.047	56.490	8.500	0.164	83.075	92.569
TT,TTC	14.226	191.690	27.270	0.525	80.118	92.782
TTT,TTC	10.646	194.620	20.720	0.399	77.215	93.014
T,TCT	10.145	261.020	26.480	0.510	73.656	93.158
TTT,TTT	0.712	220409.666	1570.107	30.233	2.305	100.000

Circuit	Specific Grade (%)	Recovery (%)
RCS Locked Cycle	91.939	64.829



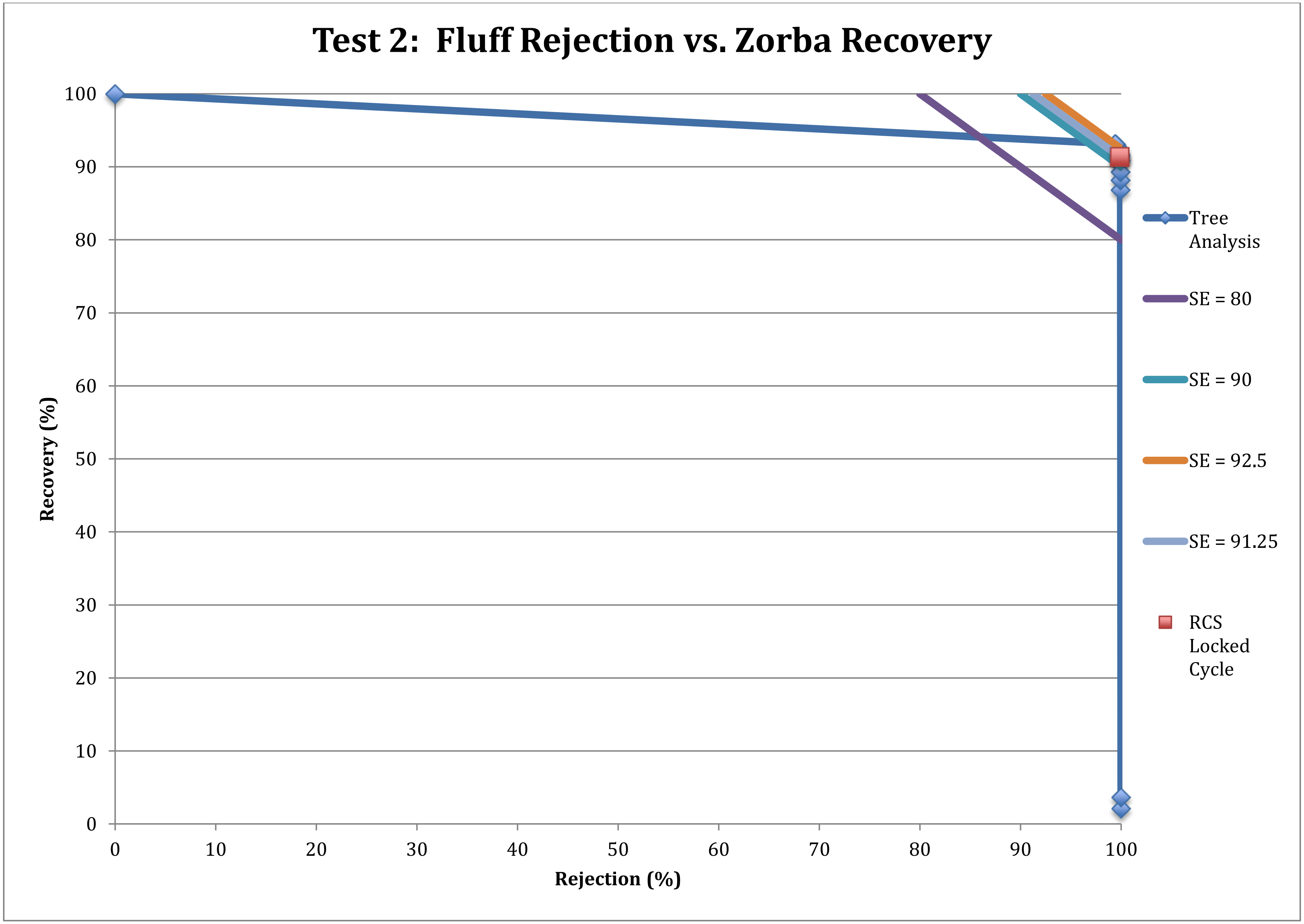
Specific Reds Grade vs. Specific Reds Recovery
Recovery (%)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
Grade (%)
Tree Analysis
Rougher Cleaner Scavenger Locked Cycle

Zorba Recovery and Fluff Rejection:

Sample	Zorba Mass (g)	Fluff Mass (g)	Total Mass (g)	Zorba Grade (%)
TTT,TTT	2059.745	218839.559	220899.304	0.932
TTT,TTC	43.320	173.900	217.220	19.943
TT,TTC	63.900	164.420	228.320	27.987
T,TTC	90.540	181.500	272.040	33.282
T,TCT	70.050	234.540	304.590	22.998
T,TCC	43.070	10.710	53.780	80.086
TCT	115.890	211.760	327.650	35.370
TCC	110.100	23.850	133.950	82.195
CTT	51.870	82.260	134.130	38.671
CTCT	37.410	6.680	44.090	84.849
CTCC	631.950	0.000	631.950	100.000
CCTT	40.150	47.990	88.140	45.553
CCTC	465.330	0.520	465.850	99.888
CC,CTT	37.790	16.050	53.840	70.189
CC,CTC	413.250	7.210	420.460	98.285
CC,CCT	460.920	18.580	479.500	96.125
CCC,CCT	339.960	13.400	353.360	96.208
CCC,CCC	25029.660	102.512	25132.172	99.592

Sample	Zorba Grade (%)	Fluff Yield (%)	Zorba Yield (%)	Cumulative Fluff Yield to T (%)	Cumulative Zorba Mass (%)	Separation Efficiency (%)
CTCC	100.000	0.000	2.099	100.000	2.099	2.099
CCTC	99.888	0.000	1.546	100.000	3.645	3.645
CCC,CCC	99.592	0.047	83.141	99.953	86.786	86.740
CC,CTC	98.285	0.003	1.373	99.950	88.159	88.109
CCC,CCT	96.208	0.006	1.129	99.944	89.288	89.232
CC,CCT	96.125	0.008	1.531	99.935	90.819	90.755
CTCT	84.849	0.003	0.124	99.932	90.944	90.876
TCC	82.195	0.011	0.366	99.922	91.309	91.231
T,TCC	80.086	0.005	0.143	99.917	91.452	91.369
CC,CTT	70.189	0.007	0.126	99.909	91.578	91.487
CCTT	45.553	0.022	0.133	99.888	91.711	91.599
CTT	38.671	0.037	0.172	99.850	91.884	91.734
TCT	35.370	0.096	0.385	99.754	92.269	92.023
T,TTC	33.282	0.082	0.301	99.672	92.569	92.241
TT,TTC	27.987	0.075	0.212	99.597	92.782	92.378
T,TCT	22.998	0.107	0.233	99.490	93.014	92.505
TTT,TTC	19.943	0.079	0.144	99.411	93.158	92.569
TTT,TTT	0.932	99.411	6.842	0.000	100.000	0.000

Circuit	Fluff Rejection (%)	Zorba Recovery (%)	Separation Efficiency (%)	Theoretical Efficiency (%)
RCS Locked Cycle	99.866	91.375	91.241	98.565



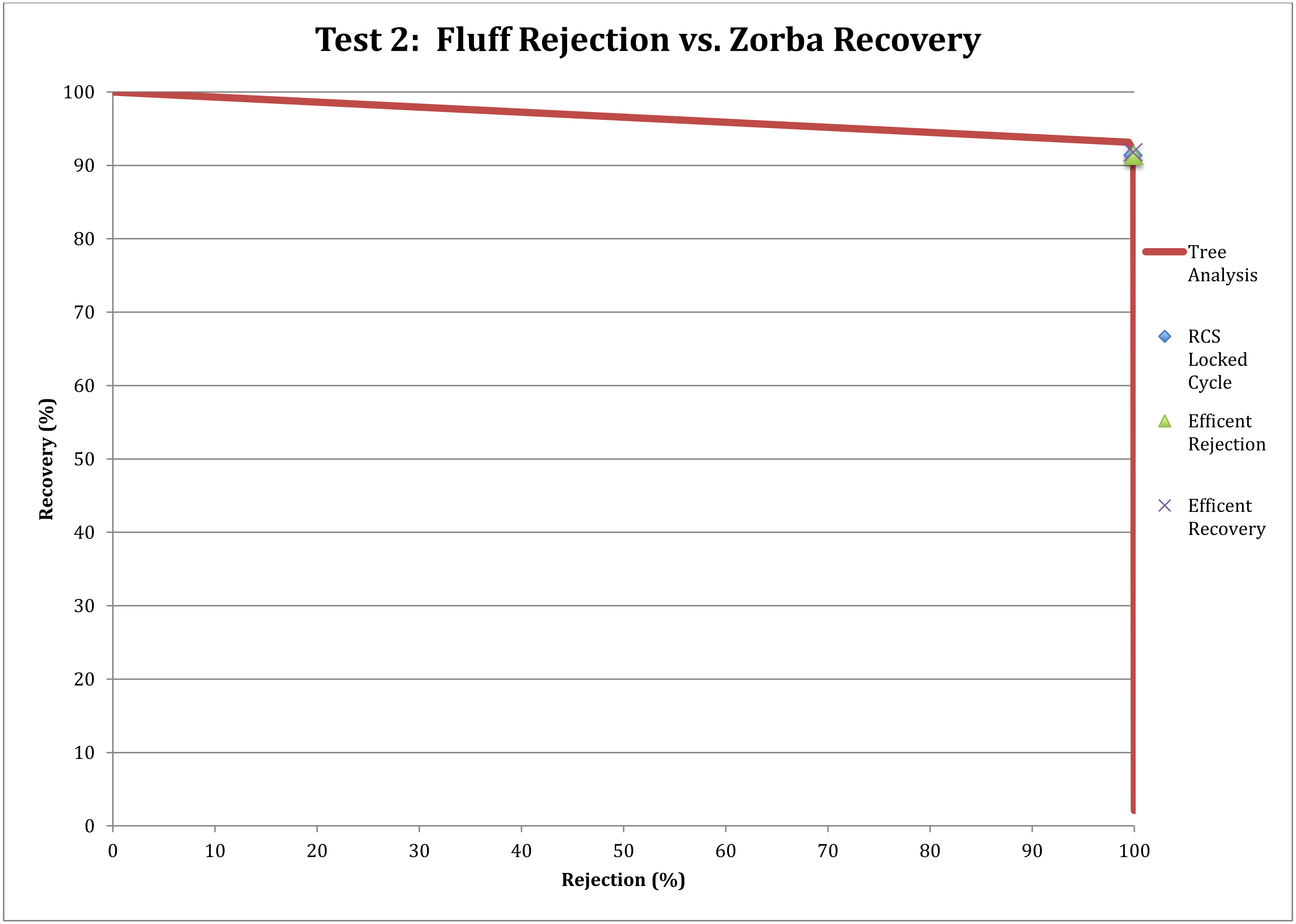
Test 2: Fluff Rejection vs. Zorba Recovery
Recovery (%)
Rejection (%)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
Tree Analysis
SE = 80
SE = 90
SE = 92.5
SE = 91.25
RCS Locked Cycle

Rejection Efficiency, Recovery Efficiency, and Spline Fitting

Sample	Fluff Rejection (x)	Cumulative Zorba Mass (y)	s	dy	dx	m
C,TCC	100.000	2.099	-6543.5045	1.5457	-0.0002	
C,CTC	100.000	3.645	-1785.3930	83.1415	-0.0466	-4164.4488
CCC,CCC	99.953	86.786	-419.1122	1.3727	-0.0033	-1102.2526
CC,CTC	99.950	88.159	-185.5136	1.1293	-0.0061	-302.3129
CCC,CCT	99.944	89.288	-181.3980	1.5310	-0.0084	-183.4558
CC,CCT	99.935	90.819	-40.9509	0.1243	-0.0030	-111.1745
C,TCT	99.932	90.944	-33.7561	0.3657	-0.0108	-37.3535
TCC	99.922	91.309	-29.4061	0.1431	-0.0049	-31.5811
T,TCC	99.917	91.452	-17.2169	0.1255	-0.0073	-23.3115
CC,CTT	99.909	91.578	-6.1177	0.1334	-0.0218	-11.6673
C,CTT	99.888	91.711	-4.6108	0.1723	-0.0374	-5.3643
CTT	99.850	91.884	-4.0018	0.3850	-0.0962	-4.3063
TCT	99.754	92.269	-3.6477	0.3007	-0.0824	-3.8247
T,TTC	99.672	92.569	-2.8418	0.2123	-0.0747	-3.2448
TT,TTC	99.597	92.782	-2.1840	0.2327	-0.1065	-2.5129
T,TCT	99.490	93.014	-1.8216	0.1439	-0.0790	-2.0028
TTT,TTC	99.411	93.158	-0.0688	6.8419	-99.4113	-0.9452
TTT,TTT	0.000	100.000				

Sample	a	b	c	d
C,TCC	2.0992	0.0000	65473634.3160	159905255229.3940
C,CTC	3.6449	-4164.4488	-87506.5733	-782053.4885
CCC,CCC	86.7863	-1102.2526	-381491.2049	-52794354.0003
CC,CTC	88.1590	-302.3129	-38037.5680	-3096641.5480
CCC,CCT	89.2883	-183.4558	7832.4581	956873.9985
CC,CCT	90.8193	-111.1745	-45097.9828	-7235546.3134
C,TCT	90.9436	-37.3535	-463.3406	-12118.6404
TCC	91.3093	-31.5811	358.6142	165596.5808
T,TCC	91.4524	-23.3115	-910.6701	-10253.0568
CC,CTT	91.5779	-11.6673	-474.5719	-10091.9068
C,CTT	91.7113	-5.3643	-32.1753	-321.4788
CTT	91.8836	-4.3063	-4.4908	-13.7749
TCT	92.2685	-3.8247	0.5920	33.2256
T,TTC	92.5693	-3.2448	-6.3851	-13.2616
TT,TTC	92.7815	-2.5129	-4.4740	-13.0148
T,TCT	93.0142	-2.0028	6.5061	111.3953
TTT,TTC	93.1581	-0.9452		
TTT,TTT				

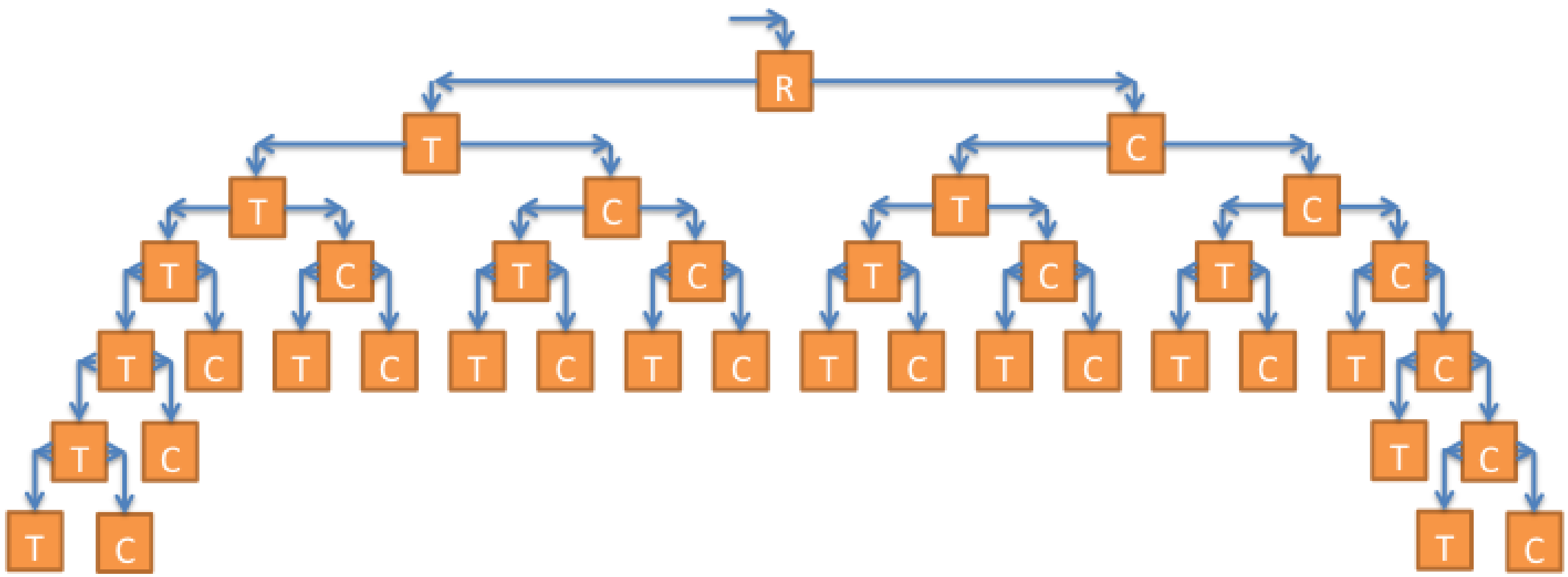
Test	Fluff Rejection (%)	Zorba Recovery (%)	Efficient Rejection (%)	Efficient Recovery (%)	Rejection Efficiency (%)	Recovery Efficiency
RCS Locked Cycle	99.866	91.375	99.920	91.815	99.946	99.520



Test 2: Fluff Rejection vs. Zorba Recovery
Recovery (%)
Rejection (%)
0
10
20
30
40
50
60
70
80
90
100
Tree Analysis
RCS Locked Cycle
Efficent Rejection
Efficent Recovery

APPENDIX E: TREE ANALYSIS DATA FOR TEST 3

Tree Sample Diagram:

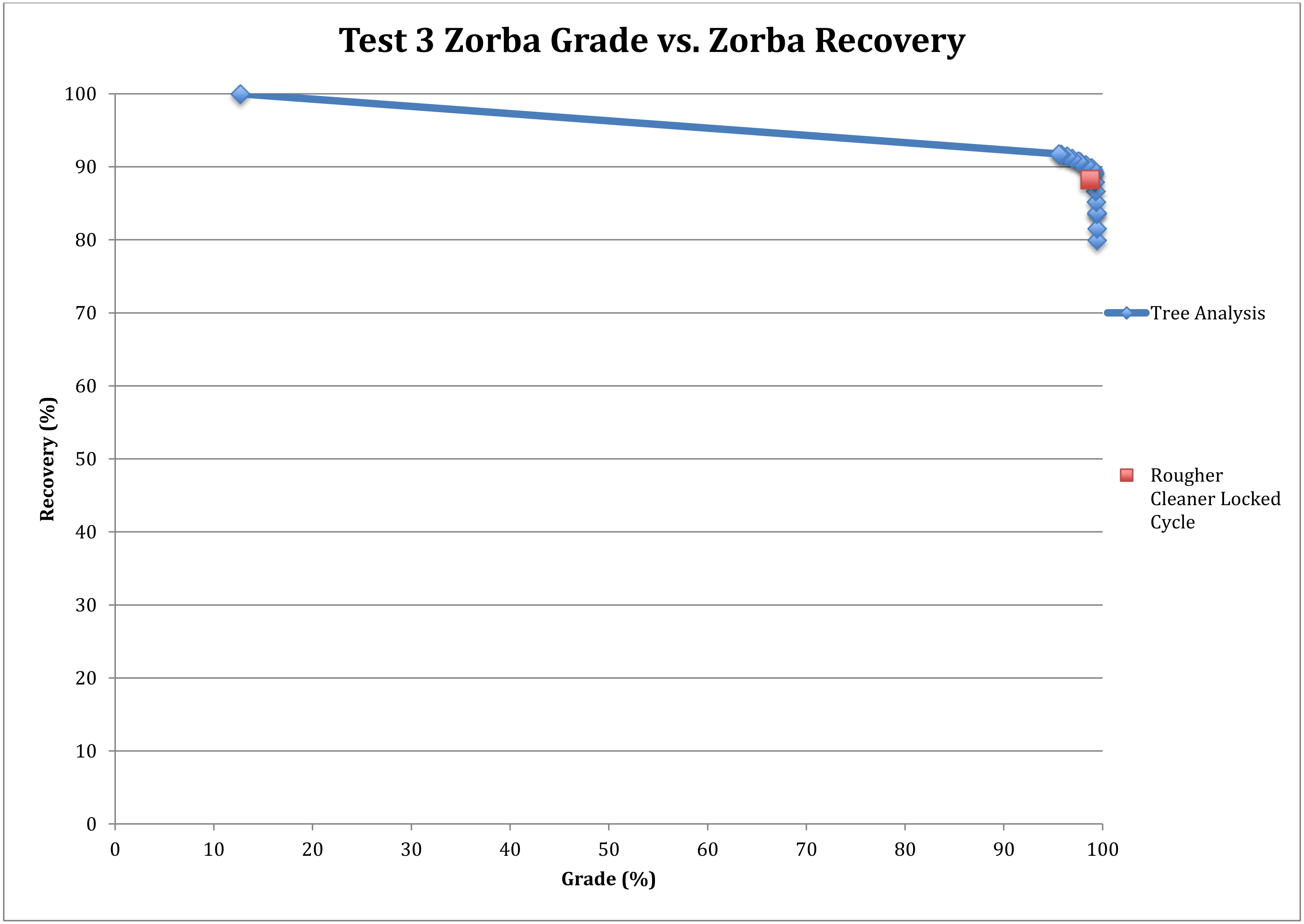


Zorba Grade and Recovery:

Sample	Reds Mass (g)	Fluff Mass (g)	Zorba Metals (g)	Total Mass (g)
TTT,TTT	1880.82	225258.06	2713.43	227971.49
TTT,TTC	28.77	169.11	95.54	264.65
TT,TTC	34.37	180.90	124.23	305.13
T,TTC	55.69	182.53	141.44	323.96
T,TCT	45.61	199.57	120.80	320.37
T,TCC	28.77	15.23	92.07	107.30
T,CTT	33.61	201.37	87.01	288.38
T,CTC	27.85	7.62	69.41	77.03
T,CCT	26.69	39.95	78.02	117.97
T,CCC	101.97	25.39	352.23	377.62
C,TTT	6.16	77.22	20.91	98.13
C,TTC	25.57	0.69	41.30	41.99
C,TCT	15.86	17.32	53.91	71.23
C,TCC	103.93	3.76	514.56	518.32
C,CTT	10.48	54.70	37.08	91.78
C,CTC	148.61	7.64	674.79	682.43
C,CCT	52.58	23.75	418.94	442.69
CC,CCT	42.52	18.02	489.76	507.78
CCC,CCT	134.31	19.43	482.06	501.49
CCC,CCC	3270.40	151.51	26342.81	26494.31

Sample	Zorba Grade (%)	Total Mass (g)	Zorba Mass (g)	Zorba Yield (%)	Cumulative Grade (%)	Cumulative Zorba Mass (%)
CCC,CCC	99.428	26494.315	26342.809	79.947	99.428	79.947
C,TCC	99.275	518.320	514.560	1.562	99.425	81.509
C,CTC	98.880	682.430	674.790	2.048	99.412	83.557
C,TTC	98.357	41.990	41.300	0.125	99.410	83.682
CC,CCT	96.451	507.780	489.760	1.486	99.357	85.168
CCC,CCT	96.126	501.490	482.060	1.463	99.301	86.631
C,CCT	94.635	442.690	418.940	1.271	99.230	87.903
T,CCC	93.276	377.620	352.230	1.069	99.154	88.972
T,CTC	90.108	77.030	69.410	0.211	99.130	89.182
T,TCC	85.806	107.300	92.070	0.279	99.082	89.462
C,TCT	75.684	71.230	53.910	0.164	99.026	89.625
T,CCT	66.135	117.970	78.020	0.237	98.897	89.862
T,TTC	43.659	323.963	141.438	0.429	98.305	90.291
TT,TTC	40.714	305.130	124.230	0.377	97.731	90.668
C,CTT	40.404	91.784	37.084	0.113	97.559	90.781
T,TCT	37.706	320.370	120.800	0.367	96.940	91.148
TTT,TTC	36.101	264.650	95.540	0.290	96.425	91.438
T,CTT	30.172	288.380	87.010	0.264	95.819	91.702
C,TTT	21.308	98.130	20.910	0.063	95.588	91.765
TTT,TTT	1.190	227971.488	2713.428	8.235	12.693	100.000

Circuit	Grade (%)	Recovery (%)
R-C Locked Cycle	98.730	88.242

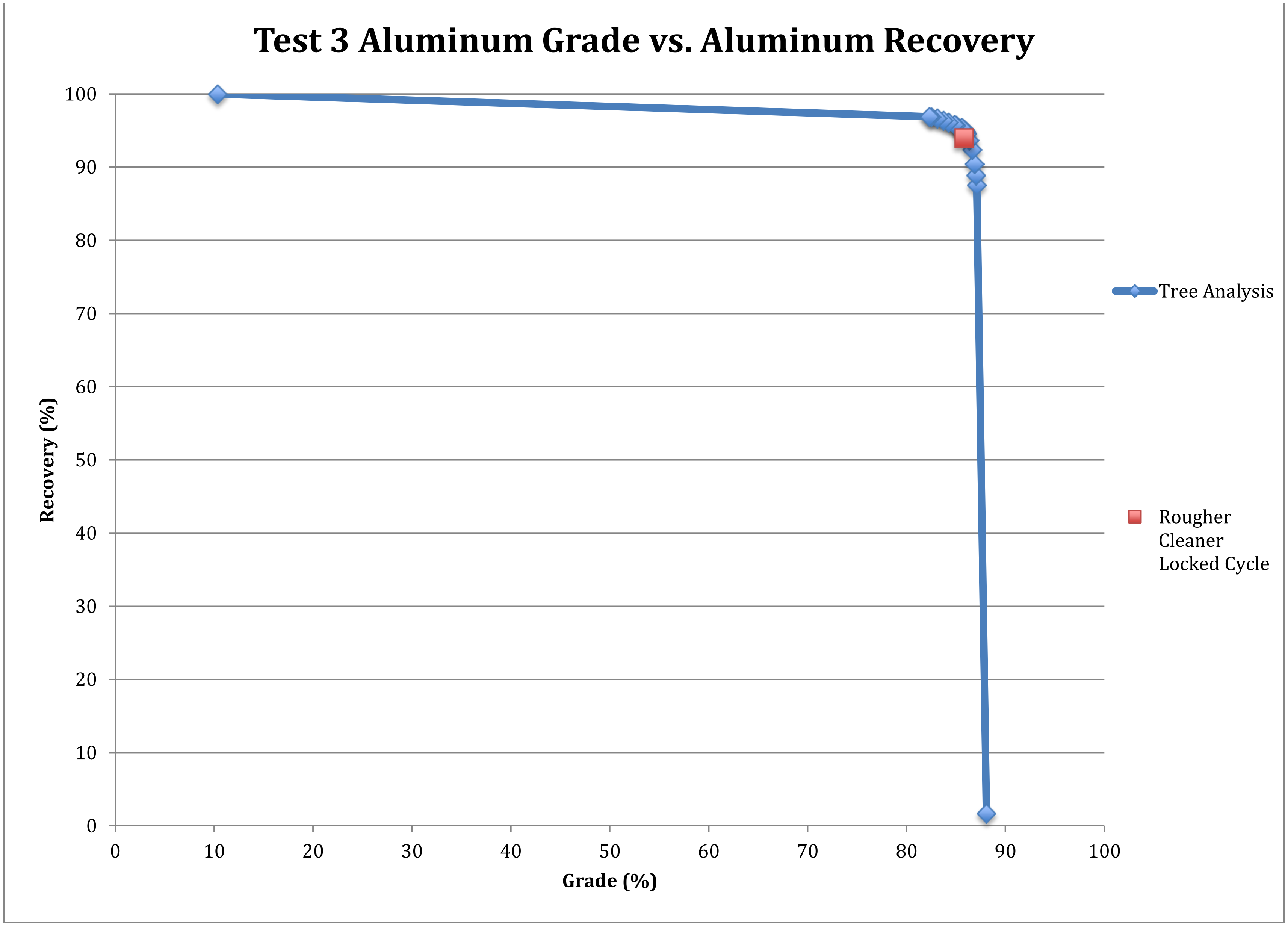

Test 3 Zorba Grade vs. Zorba Recovery
Recovery (%)
Grade (%)
0
10
20
30
40
50
60
70
80
90
100
Tree Analysis
Rougher Cleaner Locked Cycle

Aluminum Grade and Recovery:

Sample	Al Mass (g)	Fluff Mass (g)	Total Mass (g)	Aluminum Grade (%)
TTT,TTT	832.606	225258.060	227971.488	0.365
TTT,TTC	66.770	169.110	264.650	25.230
TT,TTC	89.860	180.900	305.130	29.450
T,TTC	85.749	182.525	323.963	26.469
T,TCT	75.190	199.570	320.370	23.470
T,TCC	63.300	15.230	107.300	58.993
T,CTT	53.400	201.370	288.380	18.517
T,CTC	41.560	7.620	77.030	53.953
T,CCT	51.330	39.950	117.970	43.511
T,CCC	250.260	25.390	377.620	66.273
C,TTT	14.750	77.220	98.130	15.031
C,TTC	15.730	0.690	41.990	37.461
C,TCT	38.050	17.320	71.230	53.419
C,TCC	410.630	3.760	518.320	79.223
C,CTT	26.600	54.700	91.784	28.981
C,CTC	526.180	7.640	682.430	77.104
C,CCT	366.360	23.750	442.690	82.758
CC,CCT	447.240	18.020	507.780	88.078
CCC,CCT	347.750	19.430	501.490	69.343
CCC,CCC	23072.411	151.506	26494.315	87.084

Sample	Al Grade (%)	Total Mass (g)	Al Mass (g)	Al Yield (%)	Cumulative Grade (%)	Cumulative Al Mass (%)
CC,CCT	88.078	507.780	447.240	1.664	88.078	1.664
CCC,CCC	87.084	26494.315	23072.411	85.849	87.103	87.513
C,CCT	82.758	442.690	366.360	1.363	87.033	88.876
C,TCC	79.223	518.320	410.630	1.528	86.888	90.404
C,CTC	77.104	682.430	526.180	1.958	86.655	92.361
CCC,CCT	69.343	501.490	347.750	1.294	86.357	93.655
T,CCC	66.273	377.620	250.260	0.931	86.100	94.587
T,TCC	58.993	107.300	63.300	0.236	86.002	94.822
T,CTC	53.953	77.030	41.560	0.155	85.919	94.977
C,TCT	53.419	71.230	38.050	0.142	85.841	95.118
T,CCT	43.511	117.970	51.330	0.191	85.674	95.309
C,TTC	37.461	41.990	15.730	0.059	85.607	95.368
TT,TTC	29.450	305.130	89.860	0.334	85.040	95.702
C,CTT	28.981	91.784	26.600	0.099	84.871	95.801
T,TTC	26.469	323.963	85.749	0.319	84.254	96.120
TTT,TTC	25.230	264.650	66.770	0.248	83.748	96.369
T,TCT	23.470	320.370	75.190	0.280	83.130	96.648
T,CTT	18.517	288.380	53.400	0.199	82.539	96.847
C,TTT	15.031	98.130	14.750	0.055	82.330	96.902
TTT,TTT	0.365	227971.488	832.606	3.098	10.353	100.000

Circuit	Al Grade (%)	Recovery (%)
Rougher Cleaner Locked Cycle	85.791	94.009

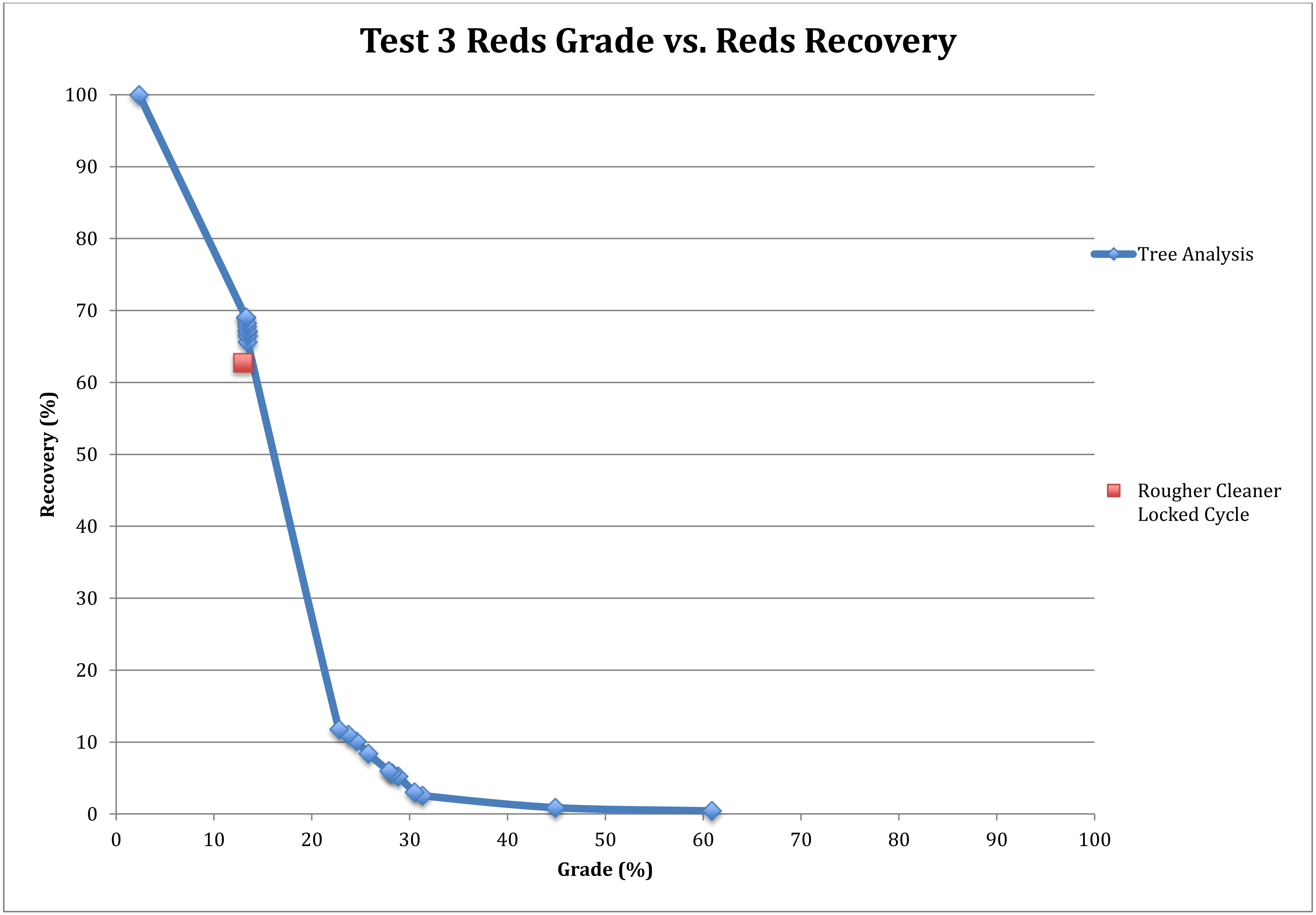

Test 3 Aluminum Grade vs. Aluminum Recovery
Recovery (%)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
Grade (%)
Tree Analysis
Rougher Cleaner Locked Cycle

Reds Grade and Recovery:

Sample	Reds Mass (g)	Fluff Mass (g)	Total Mass (g)	Reds Grade (%)
TTT,TTT	1880.822	225258.060	227971.488	0.825
TTT,TTC	28.770	169.110	264.650	10.871
TT,TTC	34.370	180.900	305.130	11.264
T,TTC	55.689	182.525	323.963	17.190
T,TCT	45.610	199.570	320.370	14.237
T,TCC	28.770	15.230	107.300	26.813
T,CTT	33.610	201.370	288.380	11.655
T,CTC	27.850	7.620	77.030	36.155
T,CCT	26.690	39.950	117.970	22.624
T,CCC	101.970	25.390	377.620	27.003
C,TTT	6.160	77.220	98.130	6.277
C,TTC	25.570	0.690	41.990	60.895
C,TCT	15.860	17.320	71.230	22.266
C,TCC	103.930	3.760	518.320	20.051
C,CTT	10.484	54.700	91.784	11.422
C,CTC	148.610	7.640	682.430	21.777
C,CCT	52.580	23.750	442.690	11.877
CC,CCT	42.520	18.020	507.780	8.374
CCC,CCT	134.310	19.430	501.490	26.782
CCC,CCC	3270.398	151.506	26494.315	12.344

Sample	Reds Grade (%)	Total Mass (g)	Reds Mass (g)	Reds Yield (%)	Cumulative Grade (%)	Cumulative Reds Mass (%)
C,TTC	60.895	41.990	25.570	0.421	60.895	0.421
T,CTC	36.155	77.030	27.850	0.458	44.883	0.879
T,CCC	27.003	377.620	101.970	1.679	31.288	2.558
T,TCC	26.813	107.300	28.770	0.474	30.493	3.032
CCC,CCT	26.782	501.490	134.310	2.211	28.810	5.243
T,CCT	22.624	117.970	26.690	0.439	28.213	5.682
C,TCT	22.266	71.230	15.860	0.261	27.886	5.943
C,CTC	21.777	682.430	148.610	2.446	25.777	8.390
C,TCC	20.051	518.320	103.930	1.711	24.588	10.100
T,TTC	17.190	323.963	55.689	0.917	23.738	11.017
T,TCT	14.237	320.370	45.610	0.751	22.768	11.768
CCC,CCC	12.344	26494.315	3270.398	53.837	13.448	65.606
C,CCT	11.877	442.690	52.580	0.866	13.425	66.471
T,CTT	11.655	288.380	33.610	0.553	13.408	67.024
C,CTT	11.422	91.784	10.484	0.173	13.402	67.197
TT,TTC	11.264	305.130	34.370	0.566	13.381	67.763
TTT,TTC	10.871	264.650	28.770	0.474	13.360	68.236
CC,CCT	8.374	507.780	42.520	0.700	13.279	68.936
C,TTT	6.277	98.130	6.160	0.101	13.258	69.038
TTT,TTT	0.825	227971.488	1880.822	30.962	2.340	100.000

Circuit	Grade (%)	Recovery (%)
R-C Locked Cycle	12.109	64.829

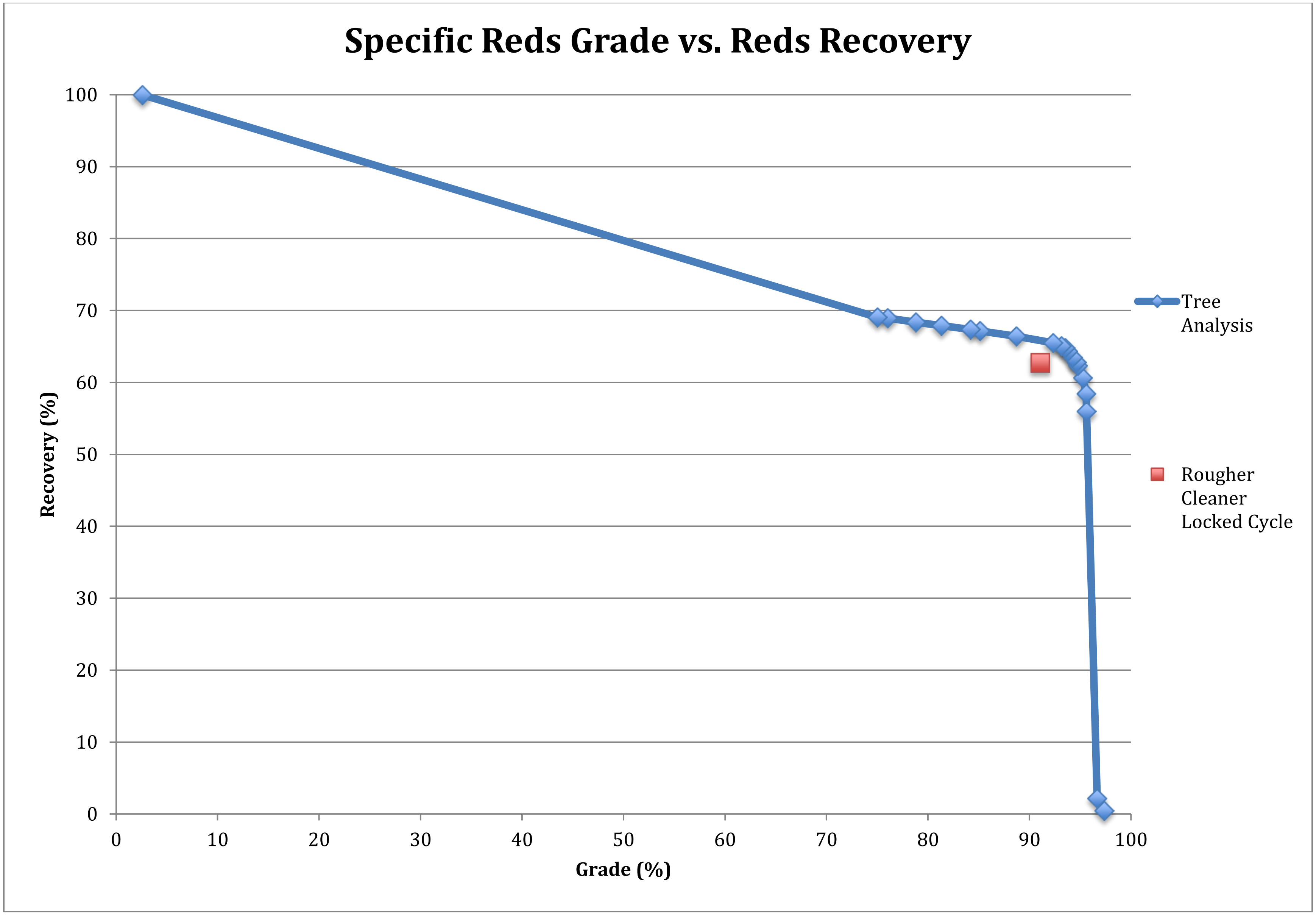

Test 3 Reds Grade vs. Reds Recovery
Recovery (%)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
Grade (%)
Tree Analysis
Rougher Cleaner Locked Cycle

Specific Reds Grade and Recovery:

Sample	Reds Mass (g)	Fluff Mass (g)	Total Relevant Mass (g)	Specific Reds Grade (%)
TTT,TTT	1880.822	225258.060	227138.882	0.828
TTT,TTC	28.770	169.110	197.880	14.539
TT,TTC	34.370	180.900	215.270	15.966
T,TTC	55.689	182.525	238.214	23.378
T,TCT	45.610	199.570	245.180	18.603
T,TCC	28.770	15.230	44.000	65.386
T,CTT	33.610	201.370	234.980	14.303
T,CTC	27.850	7.620	35.470	78.517
T,CCT	26.690	39.950	66.640	40.051
T,CCC	101.970	25.390	127.360	80.064
C,TTT	6.160	77.220	83.380	7.388
C,TTC	25.570	0.690	26.260	97.372
C,TCT	15.860	17.320	33.180	47.800
C,TCC	103.930	3.760	107.690	96.508
C,CTT	10.484	54.700	65.184	16.084
C,CTC	148.610	7.640	156.250	95.110
C,CCT	52.580	23.750	76.330	68.885
CC,CCT	42.520	18.020	60.540	70.235
CCC,CCT	134.310	19.430	153.740	87.362
CCC,CCC	3270.398	151.506	3421.904	95.572

Sample	Specific Reds Grade (%)	Total Relevant Mass (g)	Reds Mass (g)	Reds Yield (%)	Cumulative Specific Grade (%)	Cumulative Reds Mass (%)
C,TTC	97.372	26.260	25.570	0.421	97.372	0.421
C,TCC	96.508	107.690	103.930	1.711	96.678	2.132
CCC,CCC	95.572	3421.904	3270.398	53.837	95.614	55.969
C,CTC	95.110	156.250	148.610	2.446	95.593	58.416
CCC,CCT	87.362	153.740	134.310	2.211	95.266	60.627
T,CCC	80.064	127.360	101.970	1.679	94.781	62.305
T,CTC	78.517	35.470	27.850	0.458	94.638	62.764
CC,CCT	70.235	60.540	42.520	0.700	94.276	63.464
C,CCT	68.885	76.330	52.580	0.866	93.811	64.329
T,TCC	65.386	44.000	28.770	0.474	93.514	64.803
C,TCT	47.800	33.180	15.860	0.261	93.156	65.064
T,CCT	40.051	66.640	26.690	0.439	92.335	65.503
T,TTC	23.378	238.214	55.689	0.917	88.723	66.420
T,TCT	18.603	245.180	45.610	0.751	85.136	67.171
C,CTT	16.084	65.184	10.484	0.173	84.209	67.344
TT,TTC	15.966	215.270	34.370	0.566	81.314	67.909
TTT,TTC	14.539	197.880	28.770	0.474	78.807	68.383
T,CTT	14.303	234.980	33.610	0.553	76.054	68.936
C,TTT	7.388	83.380	6.160	0.101	75.030	69.038
TTT,TTT	0.828	227138.882	1880.822	30.962	2.610	100.000

Circuit	Specific Grade (%)	Recovery (%)
R-C Locked Cycle	91.061	62.727



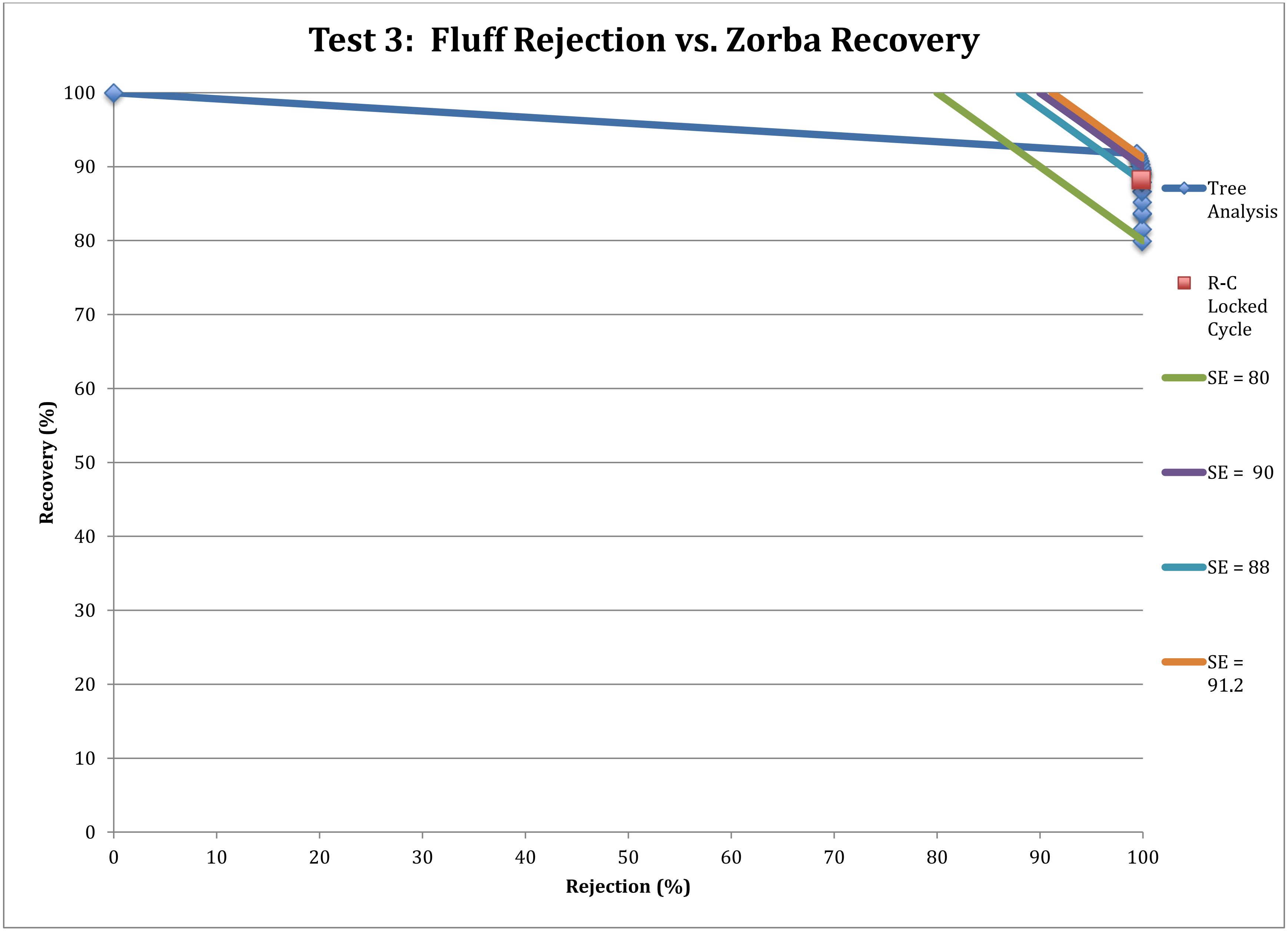
Specific Reds Grade vs. Reds Recovery
Recovery (%)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
Grade (%)
Tree Analysis
Rougher Cleaner Locked Cycle

Fluff Rejection and Zorba Recovery:

Sample	Zorba Mass (g)	Fluff Mass (g)	Total Mass (g)	Zorba Grade (%)
TTT,TTT	2713.428	225258.060	227971.488	1.190
TTT,TTC	95.540	169.110	264.650	36.101
TT,TTC	124.230	180.900	305.130	40.714
T,TTC	141.438	182.525	323.963	43.659
T,TCT	120.800	199.570	320.370	37.706
T,TCC	92.070	15.230	107.300	85.806
T,CTT	87.010	201.370	288.380	30.172
T,CTC	69.410	7.620	77.030	90.108
T,CCT	78.020	39.950	117.970	66.135
T,CCC	352.230	25.390	377.620	93.276
C,TTT	20.910	77.220	98.130	21.308
C,TTC	41.300	0.690	41.990	98.357
C,TCT	53.910	17.320	71.230	75.684
C,TCC	514.560	3.760	518.320	99.275
C,CTT	37.084	54.700	91.784	40.404
C,CTC	674.790	7.640	682.430	98.880
C,CCT	418.940	23.750	442.690	94.635
CC,CCT	489.760	18.020	507.780	96.451
CCC,CCT	482.060	19.430	501.490	96.126
CCC,CCC	26342.809	151.506	26494.315	99.428

Sample	Zorba Grade (%)	Fluff Yield (%)	Zorba Yield (%)	Cumulative Fluff Yield to T (%)	Cumulative Zorba Mass (%)	Separation Efficiency (%)
CCC,CCC	99.428	0.067	79.947	99.933	79.947	79.880
C,TCC	99.275	0.002	1.562	99.931	81.509	81.440
C,CTC	98.880	0.003	2.048	99.928	83.557	83.485
C,TTC	98.357	0.000	0.125	99.928	83.682	83.610
CC,CCT	96.451	0.008	1.486	99.920	85.168	85.088
CCC,CCT	96.126	0.009	1.463	99.911	86.631	86.543
C,CCT	94.635	0.010	1.271	99.901	87.903	87.804
T,CCC	93.276	0.011	1.069	99.890	88.972	88.861
T,CTC	90.108	0.003	0.211	99.886	89.182	89.069
T,TCC	85.806	0.007	0.279	99.880	89.462	89.341
C,TCT	75.684	0.008	0.164	99.872	89.625	89.497
T,CCT	66.135	0.018	0.237	99.854	89.862	89.716
T,TTC	43.659	0.081	0.429	99.774	90.291	90.065
TT,TTC	40.714	0.080	0.377	99.694	90.668	90.362
C,CTT	40.404	0.024	0.113	99.670	90.781	90.451
T,TCT	37.706	0.088	0.367	99.582	91.148	90.729
TTT,TTC	36.101	0.075	0.290	99.507	91.438	90.945
T,CTT	30.172	0.089	0.264	99.418	91.702	91.120
C,TTT	21.308	0.034	0.063	99.384	91.765	91.149
TTT,TTT	1.190	99.384	8.235	0.000	100.000	0.000

Circuit	Fluff Rejection (%)	Zorba Recovery (%)	Separation Efficiency (%)	Theoretical Efficiency (%)
R-C Locked Cycle	99.835	88.242	88.077	96.630

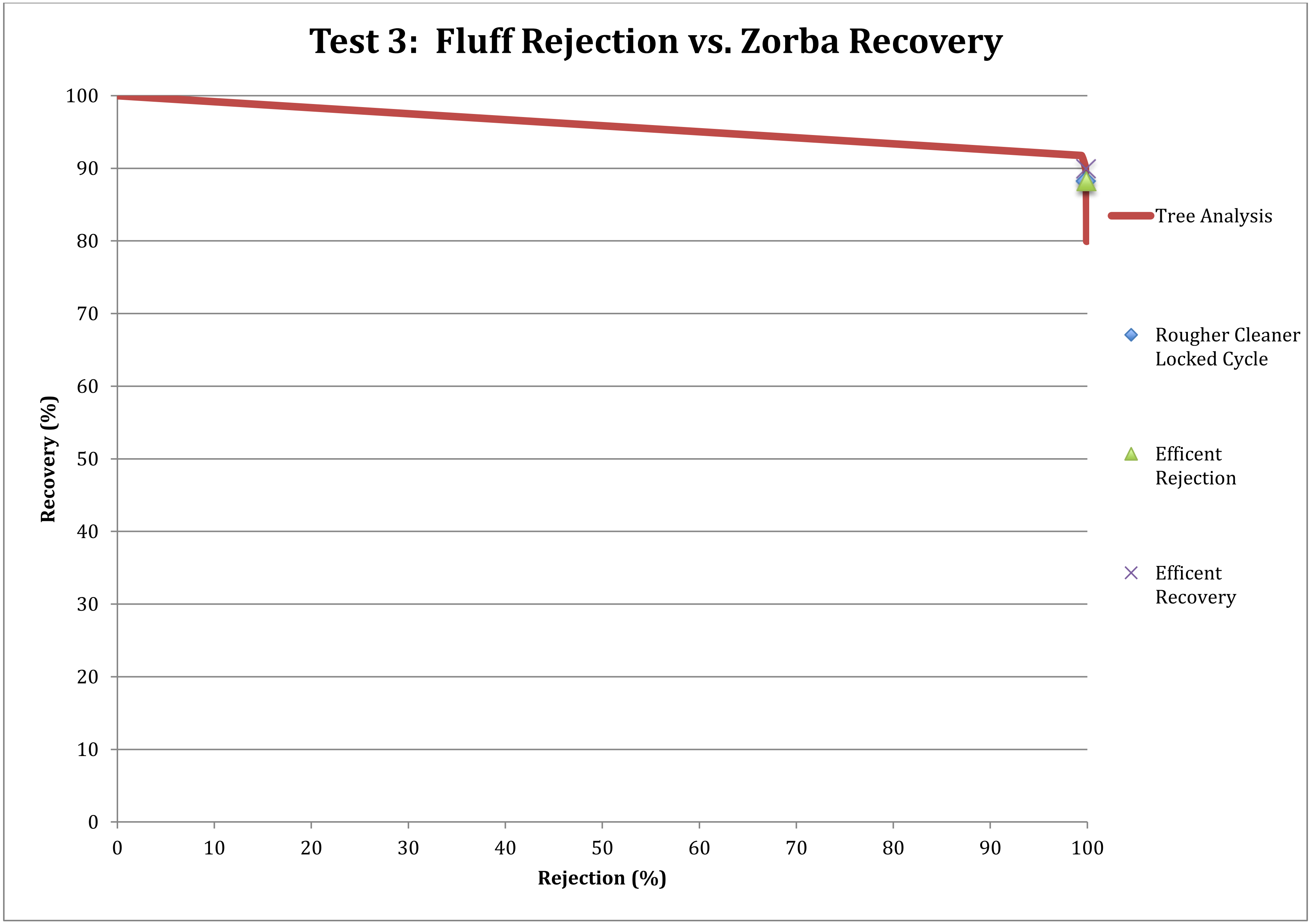


Test 3: Fluff Rejection vs. Zorba Recovery
Recovery (%)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
Rejection (%)
Tree Analysis
R-C Locked Cycle
SE = 80
SE = 90
SE = 88
SE = 91.2

Sample	Fluff Rejection (x)	Cumulative Zorba Mass (y)	s	dy	dx	m
CCC,CCC	99.933	79.947	-941.3513	1.5616	-0.0017	
C,TCC	99.931	81.509	-607.5456	2.0479	-0.0034	-774.4484
C,CTC	99.928	83.557	-411.7224	0.1253	-0.0003	-509.6340
C,TTC	99.928	83.682	-186.9529	1.4864	-0.0080	-299.3376
CC,CCT	99.920	85.168	-170.6600	1.4630	-0.0086	-178.8065
CCC,CCT	99.911	86.631	-121.3366	1.2714	-0.0105	-145.9983
C,CCT	99.901	87.903	-95.4261	1.0690	-0.0112	-108.3813
T,CCC	99.890	88.972	-62.6572	0.2107	-0.0034	-79.0416
T,CTC	99.886	89.182	-41.5836	0.2794	-0.0067	-52.1204
T,TCC	99.880	89.462	-21.4104	0.1636	-0.0076	-31.4970
C,TCT	99.872	89.625	-13.4336	0.2368	-0.0176	-17.4220
T,CCT	99.854	89.862	-5.3302	0.4292	-0.0805	-9.3819
T,TTC	99.774	90.291	-4.7238	0.3770	-0.0798	-5.0270
TT,TTC	99.694	90.668	-4.6634	0.1125	-0.0241	-4.6936
C,CTT	99.670	90.781	-4.1637	0.3666	-0.0881	-4.4135
T,TCT	99.582	91.148	-3.8861	0.2900	-0.0746	-4.0249
TTT,TTC	99.507	91.438	-2.9722	0.2641	-0.0888	-3.4292
T,CTT	99.418	91.702	-1.8626	0.0635	-0.0341	-2.4174
C,TTT	99.384	91.765	-0.0829	8.2349	-99.3842	-0.9727
TTT,TTT	0.000	100.000				

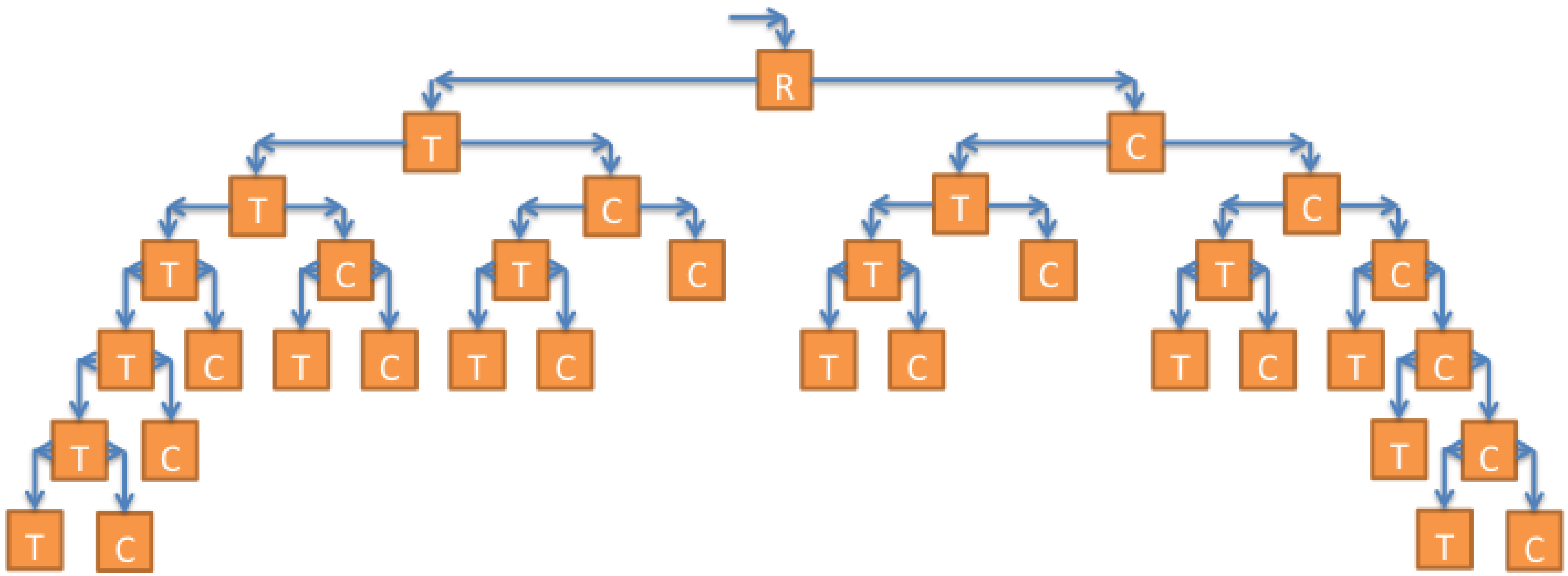
Sample	a	b	c	d
CCC,CCC	79.9471	0.0000	1235507.4796	402707361.5218
C,TCC	81.5087	-774.4484	-69982.0856	-6072026.6858
C,CTC	83.5566	-509.6340	-274081.3330	156168376.8927
C,TTC	83.6820	-299.3376	-27246.6471	-1649088.5399
CC,CCT	85.1683	-178.8065	976.2473	224733.3144
CCC,CCT	86.6313	-145.9983	-3470.7341	-106616.7119
C,CCT	87.9028	-108.3813	-850.3759	27327.3842
T,CCC	88.9717	-79.0416	-6612.8669	-517368.8261
T,CTC	89.1824	-52.1204	-1635.0913	-9971.0015
T,TCC	89.4618	-31.4970	-2117.9775	-104431.2177
C,TCT	89.6254	-17.4220	-222.6892	203.6872
T,CCT	89.8622	-9.3819	-96.8597	-578.0079
T,TTC	90.2914	-5.0270	-7.2199	-42.8598
TT,TTC	90.6685	-4.6936	7.8509	377.1598
C,CTT	90.7810	-4.4135	-4.0998	-14.3321
T,TCT	91.1476	-4.0249	2.4053	57.1629
TTT,TTC	91.4376	-3.4292	-4.0426	12.3910
T,CTT	91.7016	-2.4174	-6.4479	288.7009
C,TTT	91.7651	-0.9727	-0.0171	-0.0001
TTT,TTT				

Test	Fluff Rejection (%)	Zorba Recovery (%)	Efficient Rejection (%)	Efficient Recovery (%)	Rejection Efficiency (%)	Recovery Efficiency (%)
R-C Locked Cycle	99.835	88.242	99.896	89.979	99.939	98.070


Test 3: Fluff Rejection vs. Zorba Recovery
100
90
80
70
60
50
40
30
20
10
0
Recovery (%)
0
10
20
30
40
50
60
70
80
90
100
Rejection (%)
Tree Analysis
Rougher Cleaner Locked Cycle
Efficent Rejection
Efficent Recovery

APPENDIX F: TREE ANALYSIS FOR TEST 4

Test 4 Sample Diagram:

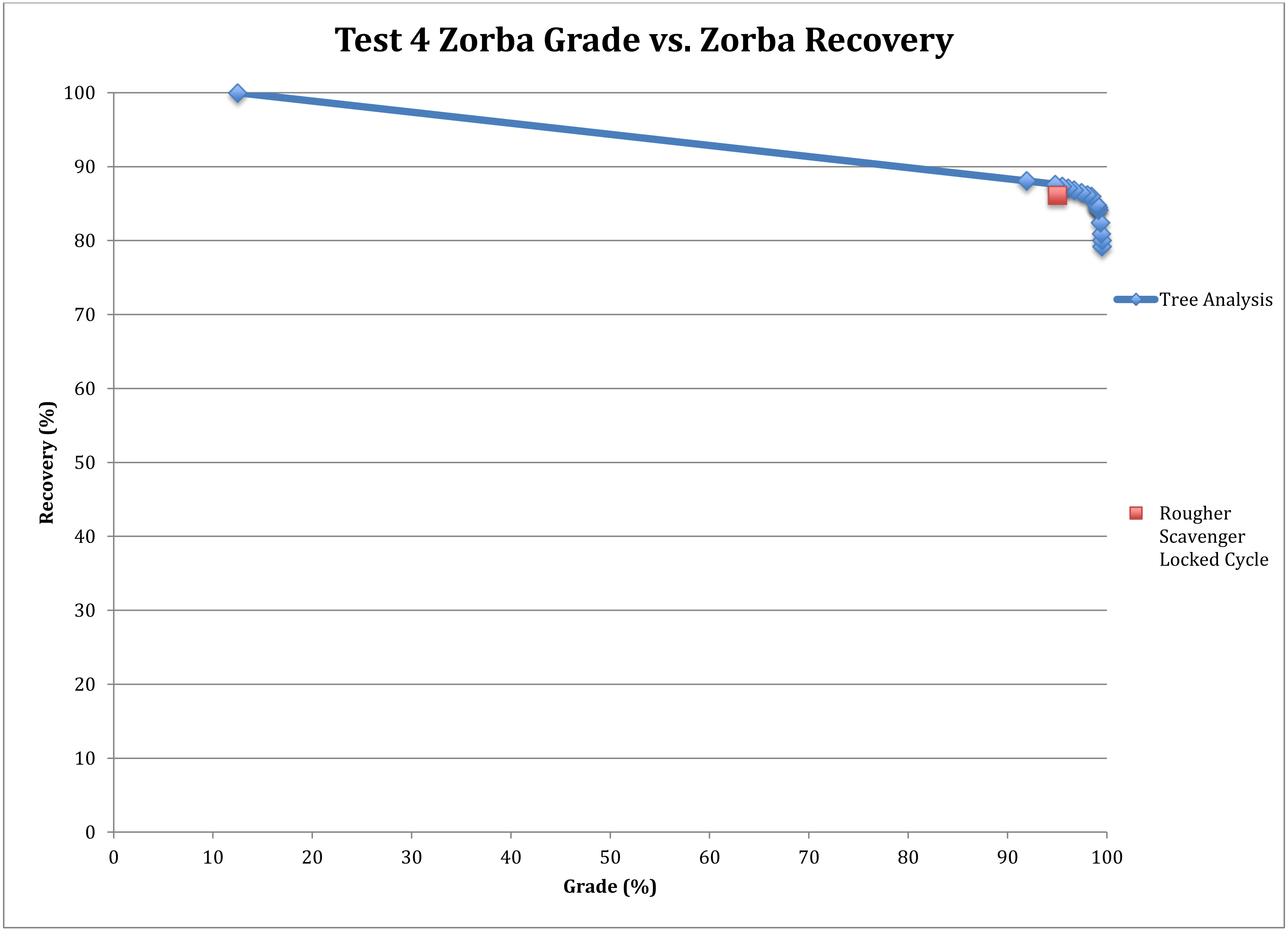


Zorba Grade and Recovery:

Sample	Reds Mass (g)	Fluff Mass (g)	Zorba Metals (g)	Total Mass (g)
TTT,TTT	2720.57	227427.28	3917.43	231344.71
TTT,TTC	35.61	191.09	80.49	271.58
TT,TTC	41.81	186.80	88.77	275.57
T,TTC	49.56	221.61	109.80	331.41
T,TCT	45.92	188.58	100.56	289.14
T,TCC	17.40	9.68	44.14	53.82
T,CCT	43.80	226.32	92.60	318.92
T,CTC	17.25	9.52	35.60	45.12
TCC	29.98	16.75	72.01	88.76
C,TTT	63.68	964.46	150.37	1114.83
C,TTC	17.87	12.80	75.27	88.07
CTC	51.36	16.14	292.05	308.19
C,CTT	27.20	116.62	64.84	181.46
C,CTC	67.00	7.50	274.92	282.42
C,CCT	62.13	54.70	560.69	615.39
CC,CCT	90.45	161.83	373.12	534.95
CCC,CCT	44.13	29.77	495.63	525.40
CCC,CCC	3032.72	124.28	26010.78	26135.06

Sample	Zorba Grade (%)	Total Mass (g)	Zorba Mass (g)	Zorba Yield (%)	Cumulative Grade (%)	Cumulative Zorba Mass (%)
CCC,CCC	99.524	26135.064	26010.780	79.207	99.524	79.207
C,CTC	97.344	282.420	274.920	0.837	99.501	80.044
CTC	94.763	308.190	292.050	0.889	99.447	80.933
CCC,CCT	94.334	525.400	495.630	1.509	99.348	82.443
C,CCT	91.111	615.390	560.690	1.707	99.166	84.150
C,TTC	85.466	88.070	75.270	0.229	99.123	84.379
T,TCC	82.014	53.820	44.140	0.134	99.090	84.514
TCC	81.129	88.760	72.010	0.219	99.033	84.733
T,CTC	78.901	45.120	35.600	0.108	99.001	84.841
CC,CCT	69.749	534.950	373.120	1.136	98.455	85.977
C,CTT	35.732	181.460	64.840	0.197	98.061	86.175
T,TCT	34.779	289.140	100.560	0.306	97.433	86.481
T,TTC	33.131	331.410	109.800	0.334	96.710	86.816
TT,TTC	32.213	275.570	88.770	0.270	96.113	87.086
TTT,TTC	29.638	271.580	80.490	0.245	95.512	87.331
T,CCT	29.035	318.920	92.600	0.282	94.813	87.613
C,TTT	13.488	1114.830	150.370	0.458	91.931	88.071
TTT,TTT	1.693	231344.709	3917.434	11.929	12.496	100.000

Circuit	Grade (%)	Recovery (%)
R-S Locked Cycle	95.004	86.171



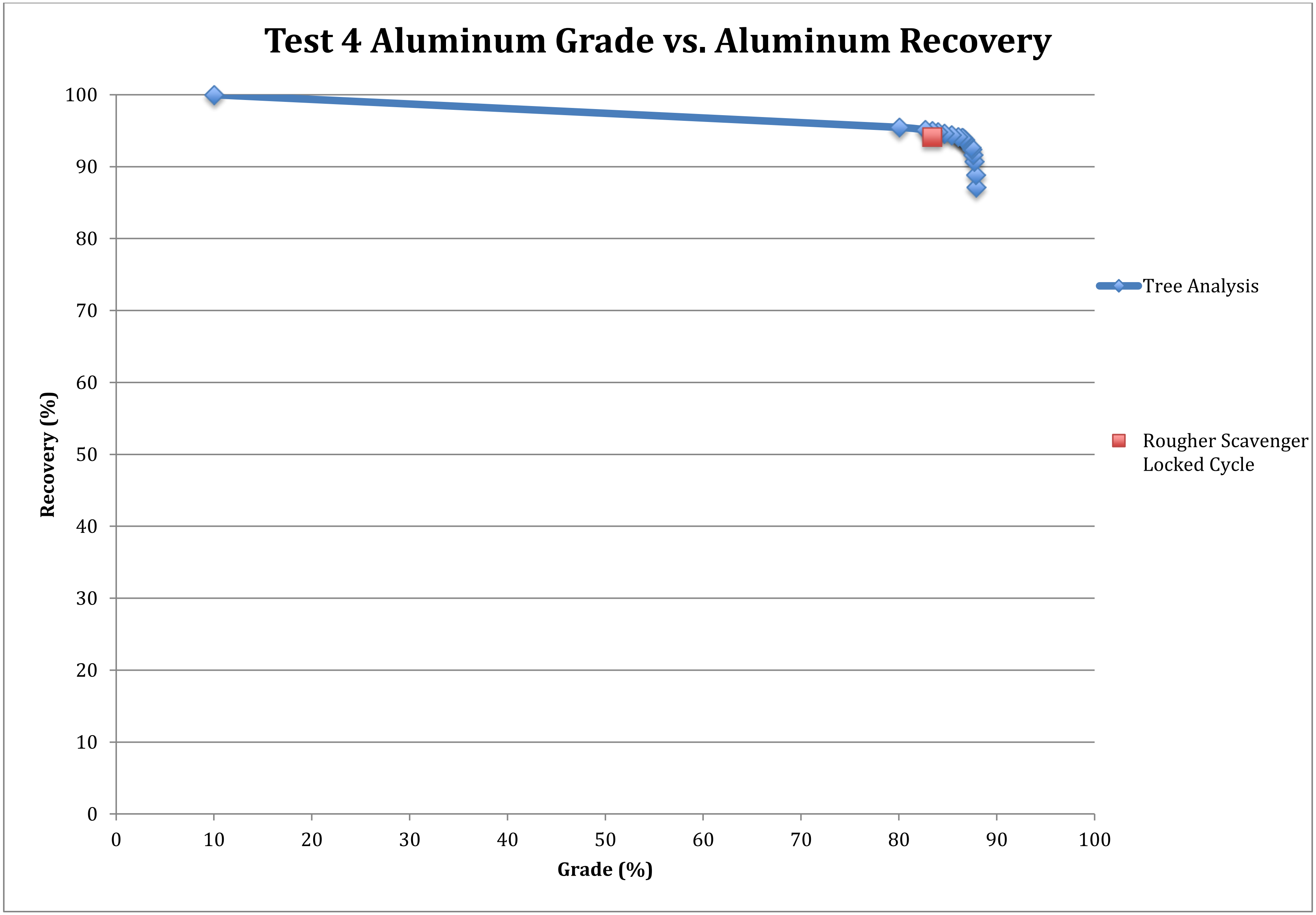
Test 4 Zorba Grade vs. Zorba Recovery
100
90
80
70
60
50
40
30
20
10
0
Recovery (%)
0
10
20
30
40
50
60
70
80
90
100
Grade (%)
Tree Analysis
Rougher Scavenger Locked Cycle

Aluminum Grade and Recovery:

Sample	Al Mass (g)	Fluff Mass (g)	Total Mass (g)	Aluminum Grade (%)
TTT,TTT	1196.866	227427.276	231344.709	0.517
TTT,TTC	44.880	191.090	271.580	16.526
TT,TTC	46.960	186.800	275.570	17.041
T,TTC	60.240	221.610	331.410	18.177
T,TCT	54.640	188.580	289.140	18.897
T,TCC	26.740	9.680	53.820	49.684
T,CCT	48.800	226.320	318.920	15.302
T,CTC	18.350	9.520	45.120	40.669
TCC	42.030	16.750	88.760	47.352
C,TTT	86.690	964.460	1114.830	7.776
C,TTC	57.400	12.800	88.070	65.175
CTC	240.690	16.140	308.190	78.098
C,CTT	37.640	116.620	181.460	20.743
C,CTC	207.920	7.500	282.420	73.621
C,CCT	498.560	54.700	615.390	81.015
CC,CCT	282.670	161.830	534.950	52.840
CCC,CCT	451.500	29.770	525.400	85.935
CCC,CCC	22978.064	124.284	26135.064	87.920

Sample	Al Grade (%)	Total Mass (g)	Al Mass (g)	Al Yield (%)	Cumulative Grade (%)	Cumulative Al Mass (%)
CCC,CCC	87.920	26135.064	22978.064	87.102	87.920	87.102
CCC,CCT	85.935	525.400	451.500	1.711	87.881	88.813
C,CCT	81.015	615.390	498.560	1.890	87.726	90.703
CTC	78.098	308.190	240.690	0.912	87.619	91.616
C,CTC	73.621	282.420	207.920	0.788	87.477	92.404
C,TTC	65.175	88.070	57.400	0.218	87.407	92.621
CC,CCT	52.840	534.950	282.670	1.072	86.758	93.693
T,TCC	49.684	53.820	26.740	0.101	86.688	93.794
TCC	47.352	88.760	42.030	0.159	86.566	93.954
T,CTC	40.669	45.120	18.350	0.070	86.494	94.023
C,CTT	20.743	181.460	37.640	0.143	86.080	94.166
T,TCT	18.897	289.140	54.640	0.207	85.414	94.373
T,TTC	18.177	331.410	60.240	0.228	84.658	94.601
TT,TTC	17.041	275.570	46.960	0.178	84.032	94.779
TTT,TTC	16.526	271.580	44.880	0.170	83.421	94.949
T,CCT	15.302	318.920	48.800	0.185	82.705	95.134
C,TTT	7.776	1114.830	86.690	0.329	80.050	95.463
TTT,TTT	0.517	231344.709	1196.866	4.537	10.038	100.000

Circuit	Al Grade (%)	Recovery (%)
R-S Locked Cycle	83.399	94.164



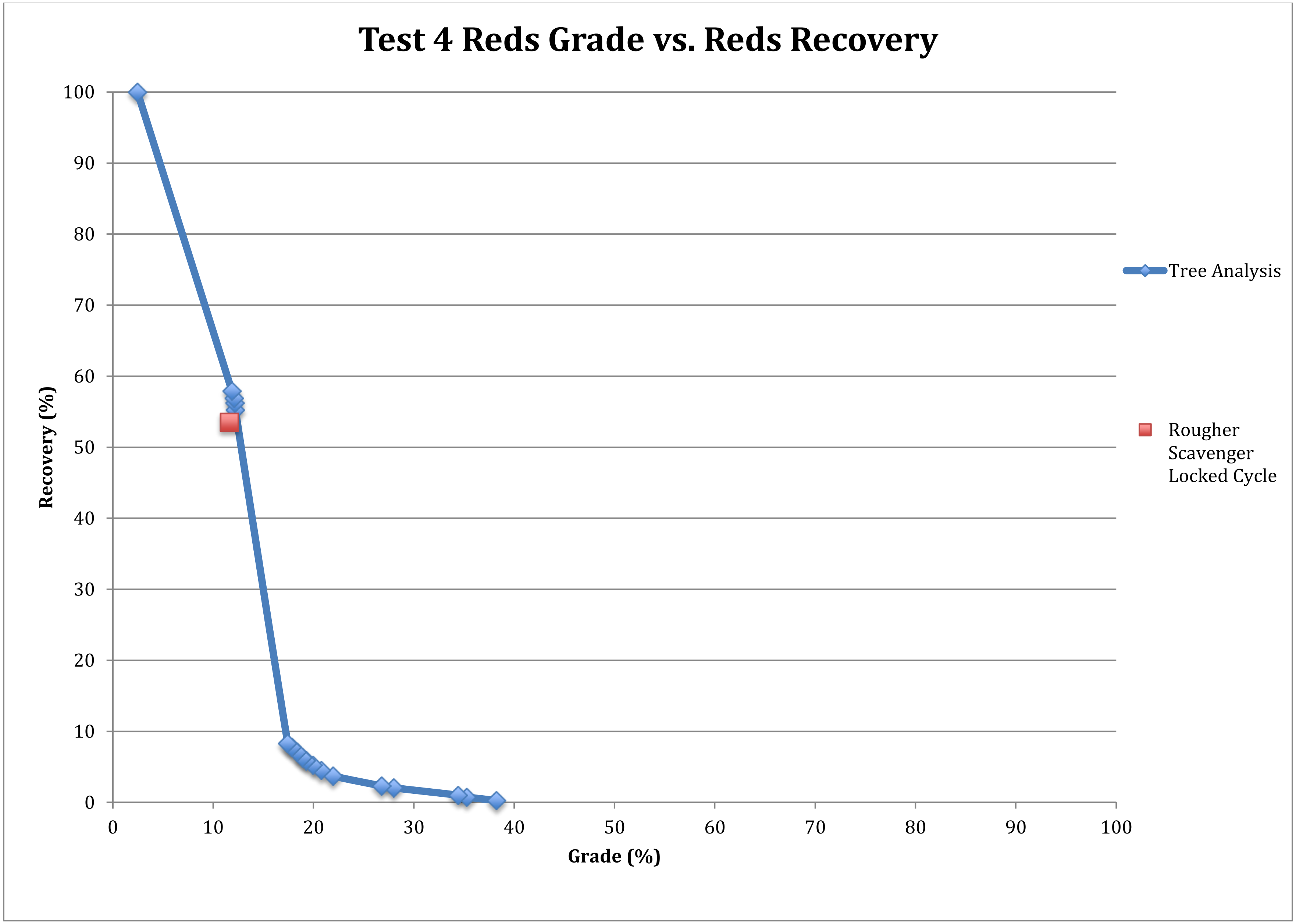
Test 4 Aluminum Grade vs. Aluminum Recovery
Recovery (%)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
Grade (%)
Tree Analysis
Rougher Scavenger Locked Cycle

Reds Grade and Recovery:

Sample	Reds Mass (g)	Fluff Mass (g)	Total Mass (g)	Reds Grade (%)
TTT,TTT	2720.568	227427.276	231344.709	1.176
TTT,TTC	35.610	191.090	271.580	13.112
TT,TTC	41.810	186.800	275.570	15.172
T,TTC	49.560	221.610	331.410	14.954
T,TCT	45.920	188.580	289.140	15.882
T,TCC	17.400	9.680	53.820	32.330
T,CCT	43.800	226.320	318.920	13.734
T,CTC	17.250	9.520	45.120	38.231
TCC	29.980	16.750	88.760	33.776
C,TTT	63.680	964.460	1114.830	5.712
C,TTC	17.870	12.800	88.070	20.291
CTC	51.360	16.140	308.190	16.665
C,CTT	27.200	116.620	181.460	14.990
C,CTC	67.000	7.500	282.420	23.724
C,CCT	62.130	54.700	615.390	10.096
CC,CCT	90.450	161.830	534.950	16.908
CCC,CCT	44.130	29.770	525.400	8.399
CCC,CCC	3032.716	124.284	26135.064	11.604

Sample	Reds Grade (%)	Total Mass (g)	Reds Mass (g)	Reds Yield (%)	Cumulative Grade (%)	Cumulative Reds Mass (%)
T,CTC	38.231	45.120	17.250	0.267	38.231	0.267
TCC	33.776	88.760	29.980	0.464	35.278	0.731
T,TCC	32.330	53.820	17.400	0.269	34.433	1.001
C,CTC	23.724	282.420	67.000	1.037	27.999	2.038
C,TTC	20.291	88.070	17.870	0.277	26.783	2.315
CC,CCT	16.908	534.950	90.450	1.400	21.951	3.715
CTC	16.665	308.190	51.360	0.795	20.788	4.511
T,TCT	15.882	289.140	45.920	0.711	19.949	5.222
TT,TTC	15.172	275.570	41.810	0.647	19.279	5.869
C,CTT	14.990	181.460	27.200	0.421	18.917	6.290
T,TTC	14.954	331.410	49.560	0.767	18.387	7.057
T,CCT	13.734	318.920	43.800	0.678	17.857	7.736
TTT,TTC	13.112	271.580	35.610	0.551	17.437	8.287
CCC,CCC	11.604	26135.064	3032.716	46.957	12.217	55.244
C,CCT	10.096	615.390	62.130	0.962	12.173	56.206
CCC,CCT	8.399	525.400	44.130	0.683	12.108	56.890
C,TTT	5.712	1114.830	63.680	0.986	11.881	57.876
TTT,TTT	1.176	231344.709	2720.568	42.124	2.458	100.000

Circuit	Grade (%)	Recovery (%)
R-S Locked Cycle	11.605	53.520

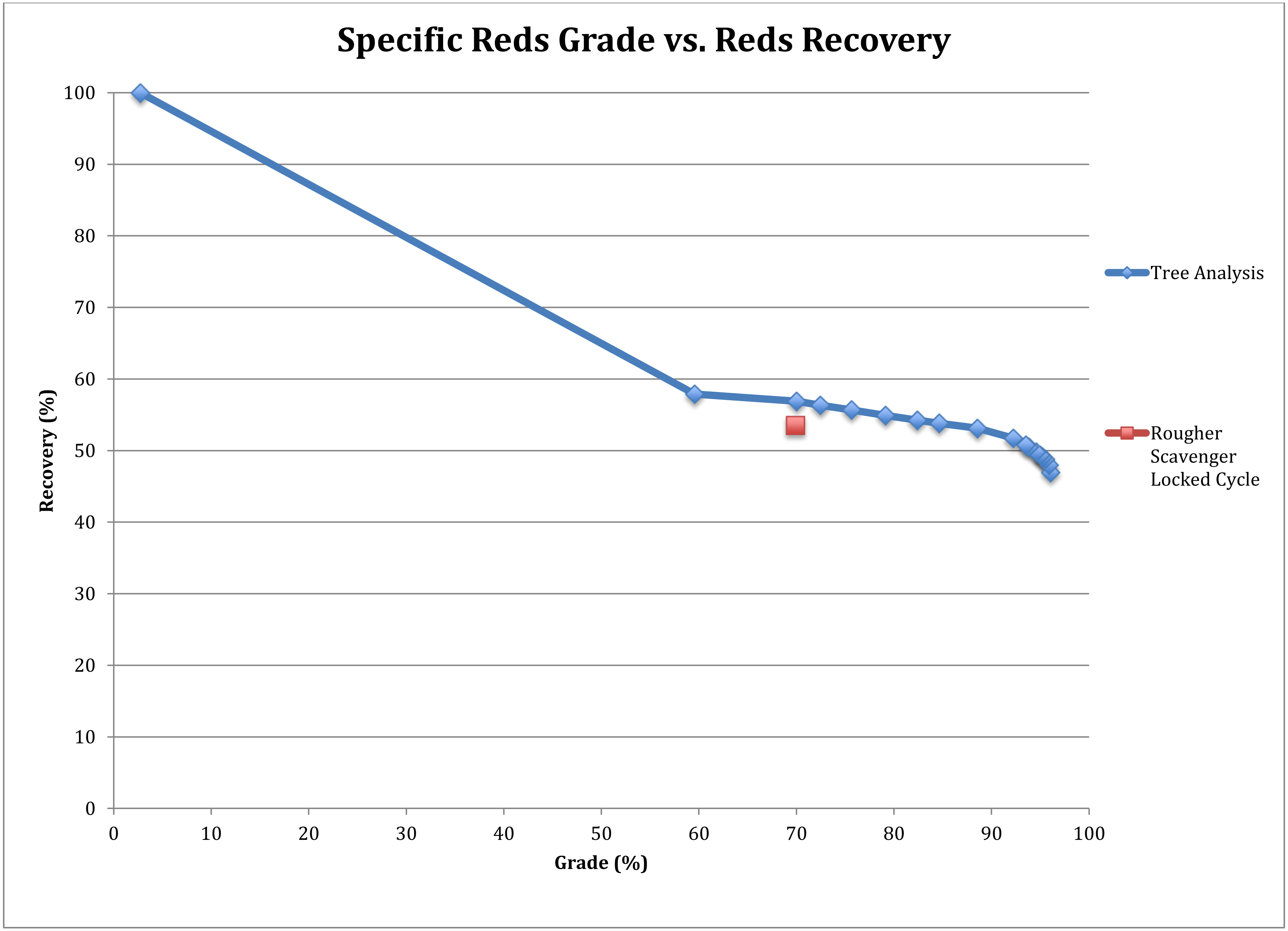

Test 4 Reds Grade vs. Reds Recovery
Recovery (%)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
Grade (%)
Tree Analysis
Rougher Scavenger Locked Cycle

Specific Reds Grade and Recovery:

Sample	Reds Mass (g)	Fluff Mass (g)	Total Relevant Mass (g)	Specific Reds Grade (%)
TTT,TTT	2720.568	227427.276	230147.844	1.182
TTT,TTC	35.610	191.090	226.700	15.708
TT,TTC	41.810	186.800	228.610	18.289
T,TTC	49.560	221.610	271.170	18.276
T,TCT	45.920	188.580	234.500	19.582
T,TCC	17.400	9.680	27.080	64.254
T,CCT	43.800	226.320	270.120	16.215
T,CTC	17.250	9.520	26.770	64.438
TCC	29.980	16.750	46.730	64.156
C,TTT	63.680	964.460	1028.140	6.194
C,TTC	17.870	12.800	30.670	58.265
CTC	51.360	16.140	67.500	76.089
C,CTT	27.200	116.620	143.820	18.913
C,CTC	67.000	7.500	74.500	89.933
C,CCT	62.130	54.700	116.830	53.180
CC,CCT	90.450	161.830	252.280	35.853
CCC,CCT	44.130	29.770	73.900	59.716
CCC,CCC	3032.716	124.284	3157.000	96.063

Sample	Specific Reds Grade (%)	Total Relevant Mass (g)	Reds Mass (g)	Reds Yield (%)	Cumulative Specific Grade (%)	Cumulative Reds Mass (%)
CCC,CCC	96.063	3157.000	3032.716	46.957	96.063	46.957
C,CTC	89.933	74.500	67.000	1.037	95.922	47.995
CTC	76.089	67.500	51.360	0.795	95.516	48.790
T,CTC	64.438	26.770	17.250	0.267	95.266	49.057
T,TCC	64.254	27.080	17.400	0.269	95.015	49.327
TCC	64.156	46.730	29.980	0.464	94.591	49.791
CCC,CCT	59.716	73.900	44.130	0.683	93.849	50.474
C,TTC	58.265	30.670	17.870	0.277	93.538	50.751
C,CCT	53.180	116.830	62.130	0.962	92.236	51.713
CC,CCT	35.853	252.280	90.450	1.400	88.563	53.113
T,TCT	19.582	234.500	45.920	0.711	84.625	53.824
C,CTT	18.913	143.820	27.200	0.421	82.402	54.245
TT,TTC	18.289	228.610	41.810	0.647	79.131	54.893
T,TTC	18.276	271.170	49.560	0.767	75.658	55.660
T,CCT	16.215	270.120	43.800	0.678	72.460	56.338
TTT,TTC	15.708	226.700	35.610	0.551	70.009	56.890
C,TTT	6.194	1028.140	63.680	0.986	59.555	57.876
TTT,TTT	1.182	230147.844	2720.568	42.124	2.732	100.000

Circuit	Specific Grade (%)	Recovery (%)
R-S Locked Cycle	69.905	53.520



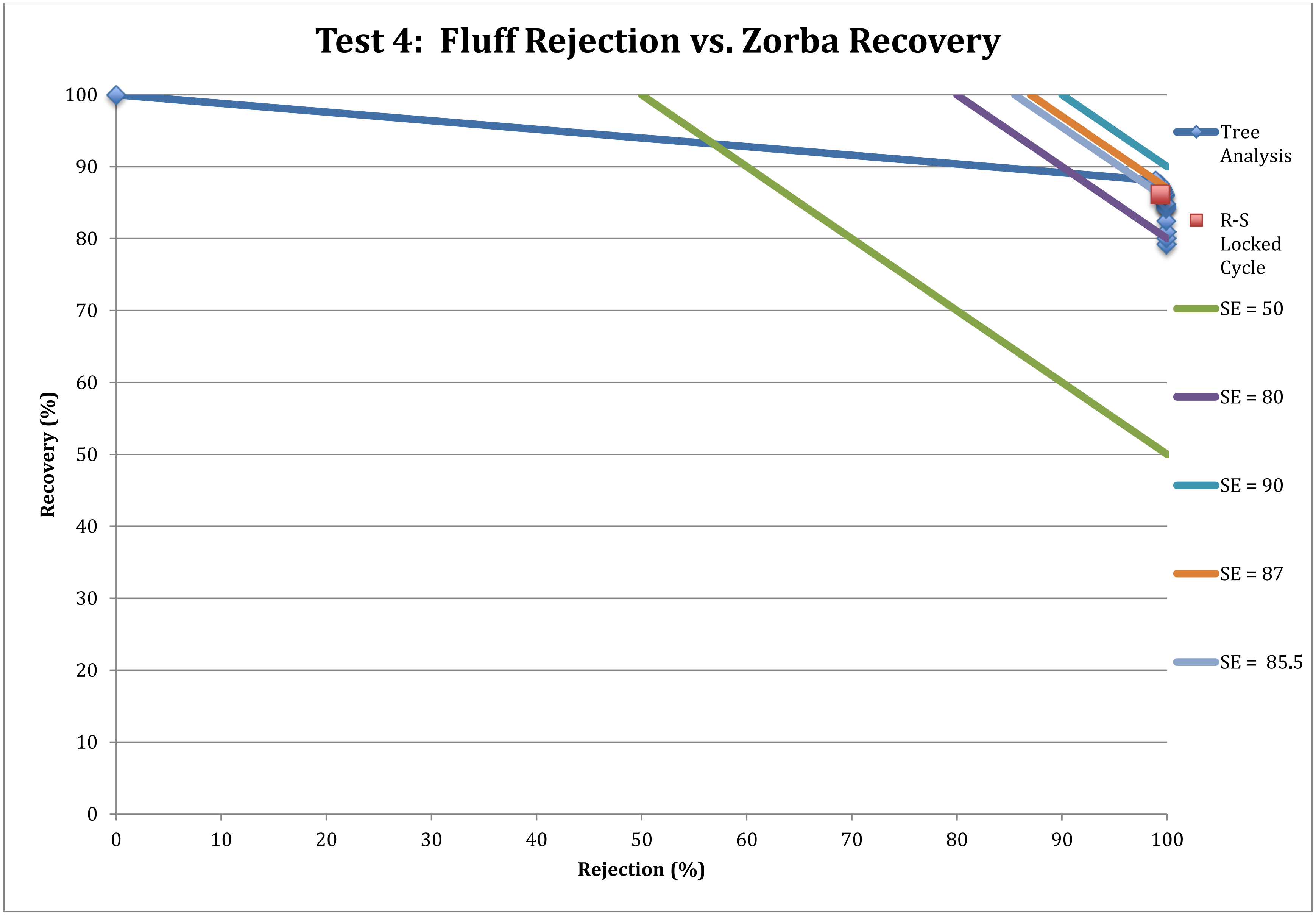
Specific Reds Grade vs. Reds Recovery
Recovery (%)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
Grade (%)
Tree Analysis
Rougher Scavenger Locked Cycle

Fluff Rejection and Zorba Recovery:

Sample	Zorba Mass (g)	Fluff Mass (g)	Total Mass (g)	Zorba Grade (%)
TTT,TTT	3917.434	227427.276	231344.709	1.693
TTT,TTC	80.490	191.090	271.580	29.638
TT,TTC	88.770	186.800	275.570	32.213
T,TTC	109.800	221.610	331.410	33.131
T,TCT	100.560	188.580	289.140	34.779
T,TCC	44.140	9.680	53.820	82.014
T,CCT	92.600	226.320	318.920	29.035
T,CTC	35.600	9.520	45.120	78.901
TCC	72.010	16.750	88.760	81.129
C,TTT	150.370	964.460	1114.830	13.488
C,TTC	75.270	12.800	88.070	85.466
CTC	292.050	16.140	308.190	94.763
C,CTT	64.840	116.620	181.460	35.732
C,CTC	274.920	7.500	282.420	97.344
C,CCT	560.690	54.700	615.390	91.111
CC,CCT	373.120	161.830	534.950	69.749
CCC,CCT	495.630	29.770	525.400	94.334
CCC,CCC	26010.780	124.284	26135.064	99.524

Sample	Zorba Grade (%)	Fluff Yield (%)	Zorba Yield (%)	Cumulative Fluff Yield to T (%)	Cumulative Zorba Mass (%)	Separation Efficiency (%)
CCC,CCC	99.524	0.054	79.207	99.946	79.207	79.153
C,CTC	97.344	0.003	0.837	99.943	80.044	79.987
CTC	94.763	0.007	0.889	99.936	80.933	80.869
CCC,CCT	94.334	0.013	1.509	99.923	82.443	82.365
C,CCT	91.111	0.024	1.707	99.899	84.150	84.049
C,TTC	85.466	0.006	0.229	99.893	84.379	84.273
T,TCC	82.014	0.004	0.134	99.889	84.514	84.403
TCC	81.129	0.007	0.219	99.882	84.733	84.615
T,CTC	78.901	0.004	0.108	99.878	84.841	84.719
CC,CCT	69.749	0.070	1.136	99.807	85.977	85.785
C,CTT	35.732	0.051	0.197	99.757	86.175	85.932
T,TCT	34.779	0.082	0.306	99.675	86.481	86.156
T,TTC	33.131	0.096	0.334	99.578	86.816	86.394
TT,TTC	32.213	0.081	0.270	99.497	87.086	86.583
TTT,TTC	29.638	0.083	0.245	99.414	87.331	86.745
T,CCT	29.035	0.098	0.282	99.316	87.613	86.928
C,TTT	13.488	0.419	0.458	98.896	88.071	86.967
TTT,TTT	1.693	98.896	11.929	0.000	100.000	0.000

Circuit	Fluff Rejection (%)	Zorba Recovery (%)	Separation Efficiency (%)	Theoretical Efficiency (%)
R-S Locked Cycle	99.353	86.171	85.524	98.340



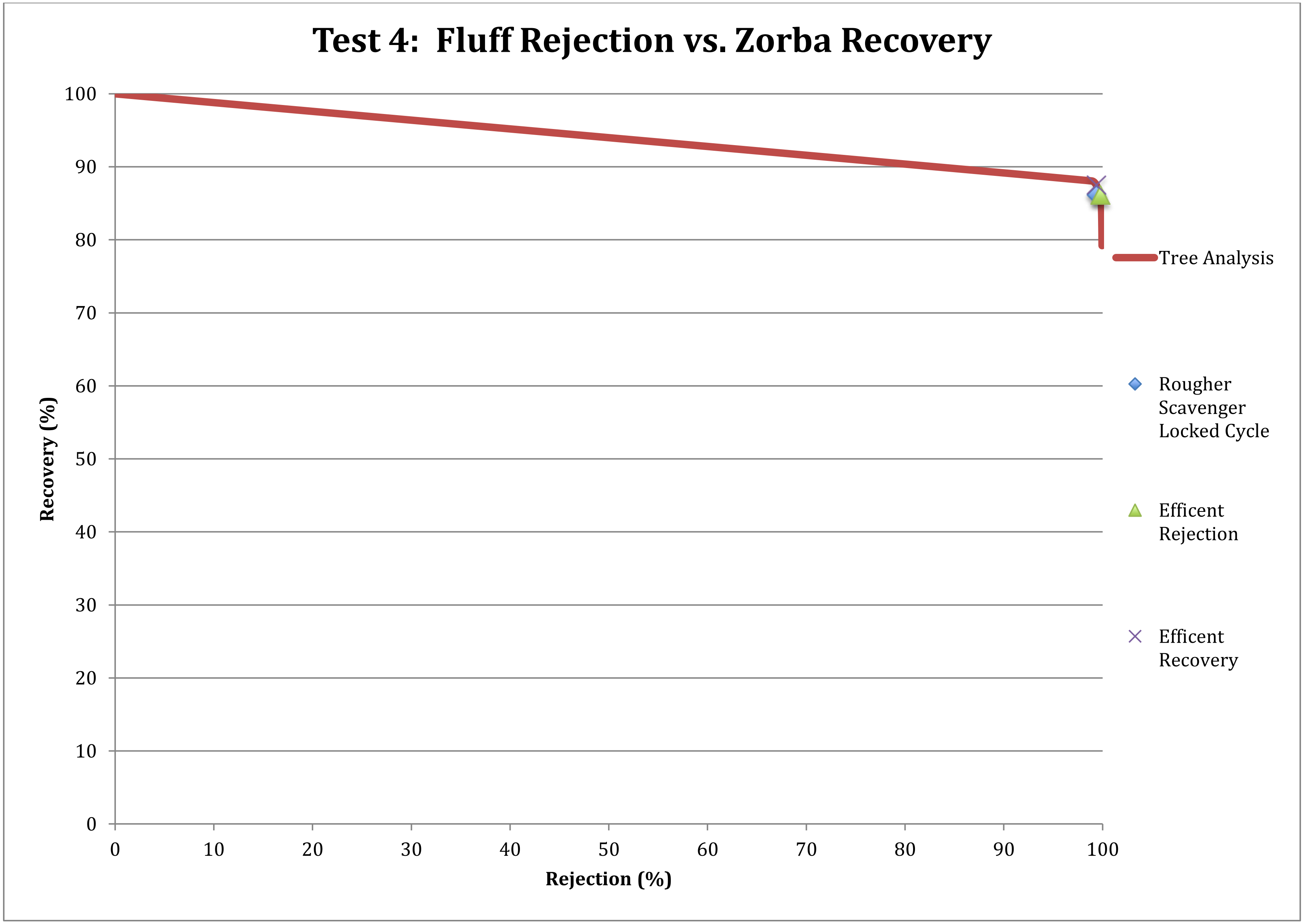
Test 4: Fluff Rejection vs. Zorba Recovery
Recovery (%)
100
90
80
70
60
50
40
30
20
10
0
0
10
20
30
40
50
60
70
80
90
100
Rejection (%)
Tree Analysis
R-S Locked Cycle
SE = 50
SE = 80
SE = 90
SE = 87
SE = 85.5

Rejection Efficiency, Recovery Efficiency, and Spline Fitting

Sample	Fluff Rejection (x)	Cumulative Zorba Mass (y)	s	dy	dx	m
CCC,CCC	99.946	79.207	-256.6949	0.8372	-0.0033	
C,CTC	99.943	80.044	-126.7144	0.8893	-0.0070	-191.7047
CTC	99.936	80.933	-116.5872	1.5093	-0.0129	-121.6508
CCC,CCT	99.923	82.443	-71.7807	1.7074	-0.0238	-94.1840
C,CCT	99.899	84.150	-41.1798	0.2292	-0.0056	-56.4802
C,TTC	99.893	84.379	-31.9322	0.1344	-0.0042	-36.5560
T,TCC	99.889	84.514	-30.1058	0.2193	-0.0073	-31.0190
TCC	99.882	84.733	-26.1870	0.1084	-0.0041	-28.1464
T,CTC	99.878	84.841	-16.1459	1.1362	-0.0704	-21.1664
CC,CCT	99.807	85.977	-3.8935	0.1974	-0.0507	-10.0197
C,CTT	99.757	86.175	-3.7342	0.3062	-0.0820	-3.8139
T,TCT	99.675	86.481	-3.4696	0.3344	-0.0964	-3.6019
T,TTC	99.578	86.816	-3.3278	0.2703	-0.0812	-3.3987
TT,TTC	99.497	87.086	-2.9497	0.2451	-0.0831	-3.1388
TTT,TTC	99.414	87.331	-2.8652	0.2820	-0.0984	-2.9075
T,CCT	99.316	87.613	-1.0918	0.4579	-0.4194	-1.9785
C,TTT	98.896	88.071	-0.1206	11.9292	-98.8962	-0.6062
TTT,TTT	0.000	100.000				

Sample	a	b	c	d
CCC,CCC	79.2068	0.0000	177343.4837	30243692.4041
C,CTC	80.0440	-191.7047	-17798.4039	-1216576.8494
CTC	80.9333	-121.6508	948.2985	103468.8932
CCC,CCT	82.4426	-94.1840	-1240.4726	-12553.9864
C,CCT	84.1500	-56.4802	-4667.0692	-344621.3257
C,TTC	84.3792	-36.5560	-1979.9757	-209419.1919
T,TCC	84.5136	-31.0190	18.2591	19720.2921
TCC	84.7329	-28.1464	266.1306	178621.6395
T,CTC	84.8413	-21.1664	-55.6322	223.2647
CC,CCT	85.9775	-10.0197	-240.0368	-2351.1867
C,CTT	86.1749	-3.8139	-0.3291	7.8302
T,TCT	86.4812	-3.6019	-2.0099	-6.6105
T,TTC	86.8155	-3.3987	0.5818	17.9087
TT,TTC	87.0858	-3.1388	-4.0426	-21.2672
TTT,TTC	87.3309	-2.9075	8.1518	87.1909
T,CCT	87.6129	-1.9785	-3.0707	-2.2805
C,TTT	88.0708	-0.6062	-0.0086	0.0000
TTT,TTT				

Test	Fluff Rejection (%)	Zorba Recovery (%)	Efficient Rejection (%)	Efficient Recovery (%)	Rejection Efficiency (%)	Recovery Efficiency (%)
R-S Locked Cycle	99.353	86.171	99.758	87.527	99.594	98.451


Test 4: Fluff Rejection vs. Zorba Recovery
100
90
80
70
60
50
40
30
20
10
0
Recovery (%)
0
10
20
30
40
50
60
70
80
90
100
Rejection (%)
Tree Analysis
Rougher Scavenger Locked Cycle
Efficent Rejection
Efficent Recovery