A Methodology for Assessing the Reusability of Recycled Organic Photoconductive Drums for Laser Printers

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Abstract

The toner cartridge manufacturing industry continues to grow at a rapid pace. This growth fuels the development of toner cartridge remanufacturing. While many remanufacturers of toner cartridges for laser printers replace the recycled organic photoconductive (OPC) drums with new aftermarket ones, others opt to reuse the recycled OPCs. The latter approach yields a savings to the remanufacturer in both material cost and waste, but since the condition of a used drum is unknown, tests must be performed on each individual OPC to determine its reusability. Typically, a recycled OPC is deemed reusable if it passes a visual inspection and/or yields an acceptable output in print testing. Unfortunately, neither of these methods produce quantitative measurements that can be used to objectively estimate the remaining life of the OPC. In this paper, a method based on a computerized OPC drum scanner for assessing the reusability of recycled OPCs is presented. The method, in conjunction with print testing, visual inspection, and historical data on the OPC type in consideration, has shown to be very effective in predicting the performance of recycled OPCs. Test results to support the validity of this method and its limitations will be discussed.

Introduction

In 1994, over 31 million laser printer cartridges were sold in the United States alone. This corresponds to retail revenue of about $3.2 billion. Considering the number of cartridges already in circulation, recycling used cartridges makes a lot of economic and environmental sense[1].

Accordingly, the toner cartridge remanufacturing industry is growing at a rapid pace. It is estimated that 29% of the 1994 cartridge sales were recycled units[1]. While many remanufacturers of toner cartridges for laser printers replace the used organic photoconductive (OPC) drums with new aftermarket ones, others opt to reuse the recycled OPCs. The latter approach yields a savings in material costs and a reduction of waste. But since the condition of a used OPC is unknown, tests must be performed on each individual OPC to determine its reusability. Typically, a recycled OPC is deemed reusable if it passes a visual inspection and/or yields an acceptable output in print testing. Unfortunately, neither of these methods produce quantitative measurements that can be used objectively to estimate the remaining life of the OPC.

In this study, a method based on instrumented measurements is developed for assessing the reusability of recycled OPCs quantitatively and objectively. By definition, a reusable OPC must perform adequately in a remanufactured toner cartridge for at least one additional cycle of use, without appreciable print quality degradation.

Other Applications

While the primary objective of this study is to develop methods for assessing the reusability of recycled OPCs, the same measurement and analysis principles are equally suited to many other applications. These techniques can provide valuable data in the development of new OPCs, and as quality control metrics in production.

Background

Failure Modes and Failure Mechanisms in OPCs

OPC failure is evidenced by a loss in print quality. Key print quality characteristics include the optical density of text and graphics, resolution, background (toner in unwanted areas), and localized repeating defects. Cartridge components other than the OPC obviously can lead to print defects, but our focus here is on the OPC. There are several failure mechanisms which may affect an OPC in use[2]:

1. Mechanical damage[3-6] (wear, fatigue, or localized defects such as pinholes or scratches)

2. Chemical damage[7] (reactive gases such as ozone, NO_x, and UV light can cause reactions, decomposition, and structural changes in the material)
3. Electrical aging[7-8] (applied electric field and charge as well as photo-effects result in the formation of space charge and boundary layers, and give rise to trapping effects and changes in contact properties)
4. Thermal and environmental aging (thermal energy and moisture in the environment can lead to chemical reactions, structural changes, relaxation of stress and rearrangement of molecules)

Practical Considerations in Drum Quality Assessment

In order for a drum assessment method to be accepted, it must be simple enough to be used in a production line, reliable, and economical. Even after a quantitative assessment tool is in place, a remanufacturer must develop accept/reject limits. A unique problem to recycling is that many recyclers are not privileged to the specifications and data of the OEM, and therefore must rely on statistical data and educated assumptions to establish accept/reject limits.

A very common drum screening method currently employed by most remanufacturers involves print testing. Although a print test provides a very practical and direct evaluation of the OPC's current quality, it is not a reliable predictive tool. Many printers have built-in control mechanisms to compensate for the degradation of OPCs. As a result, the print tests from an aging OPC continue to look good until the OPC is very close to the end of its useful life, at which time the print quality diminishes dramatically. On the other hand, properly designed instrumented testing can detect the gradual degradation process and is therefore more suitable for life prediction.

Experimental Methods

Overview

A sample of Hewlett-Packard/Canon EX OPCs were tested using various measurement techniques, facilitated by photoconductive drum scanners and other specialized test equipment. The data were analyzed to determine which (if any) measurement and analysis methods are most effective in determining OPC quality, with emphasis on useful life prediction.

Materials

The test samples consisted of 70 recycled and 4 new Hewlett-Packard/Canon EX OPCs. These samples were collected from end-users by a remanufacturer of toner cartridges. The detailed history of each cartridge is unknown.

Measurement Equipment

1. Photoconductive Drum Scanner (QEA PDT-2000LA): This equipment is used to scan OPCs for charging, discharge, and dark decay characteristics. The equipment allows the option of either corona or charge-roller charging methods. Both charging methods were used in this study.
2. Charge Roller Scanner (QEA CRT-2000): This equipment is used to characterize the charge rollers used in this study to establish their condition. These measurements help isolate the effects of the OPCs from the effects of the charge rollers on test results.
3. OPC Coating Thickness Gage (QEA ECT-100): This equipment is used to measure the thickness of OPC coating material.
4. Instrumented Toner Cartridge (QEA PDT-3000): This equipment consists of a modified toner cartridge in which an electrostatic probe is installed in place of the development roller (the modified cartridge contains no toner). The modified cartridge can be used to measure the OPC voltage in the printer during a simulated print test.
5. Image Quality Analysis System (QEA IAS-1000): This is an automated system for evaluating the test prints for density, background, and other print quality metrics.
6. Printers (Hewlett Packard Laserjet 4): These printers were used for print testing with the instrumented cartridge (see above) and for OPC life testing. The built-in continuous self-test pattern was used during life testing to generate test prints with toner coverage greater than 5%.

Test Methods

For each of the 74 OPCs, the following measurements were made:

1. Thickness. Using the ECT-100 thickness gage, the coating thickness of each OPC was measured. The ECT-100 measures the thickness from the topmost surface of the drum to the top of the metal substrate. To account for the extra base layer in the HP/Canon EX OPCs, a base layer thickness of 15 µm was assumed for all OPCs tested. Therefore, the thickness values reported in this study are the ECT-100 measurements minus 15 µm, that is, the thickness attributed to the barrier, charge generation (CGL), and charge transport (CTL) layers of the OPCs.
2. Mean Charge Acceptance. Using the PDT-2000LA, a series of charge scans was performed on each drum and the mean charge acceptance level was recorded. During a charge scan, a charging device and an electrostatic probe scan the OPC in the dark to map the surface potential of the OPC as a result of charging. The charging device was adjusted to produce a charge acceptance of 700V on a new OPC. Unlike the charging device in a printer, the PDT-2000LA employs a charger which by design is sensitive to OPC defects. Therefore, the charge acceptance measurement is expected to vary among drums of various coating thickness and quality.
3. Minimum Charge Acceptance. Using the PDT-2000LA, a series of charge scans (see description of

mean charge acceptance above) was performed on each drum and the minimum acceptance level was recorded.

4. Mean Discharge Voltage. Using the PDT-2000LA, a series of discharge scans was performed on each drum and the mean discharge level (the voltage on the drum surface when subjected first to a charging in the dark, and then exposed by a controlled light source) was recorded. The same exposure energy was used for each measurement, and was selected to discharge the OPCs to approximately 50% of the acceptance voltage.
5. Dark Decay Ratio. Using the PDT-2000LA, a dark decay measurement was performed on each drum. During a dark decay measurement, the drum is subjected to charging and then the voltage on the drum surface is monitored in the dark for a period of time. The dark decay ratio is here defined as the voltage measured 1 second after charging, divided by the acceptance voltage (measured immediately after charging).
6. Mean In-Situ Charge Acceptance. Using the PDT-3000 instrumented cartridge, the voltage on the surface of each drum inside a printer was sampled at 100 Hz while simulating the printing of a white page. The mean of 300 consecutive data points was recorded.
7. In-Situ Charge Acceptance Standard Deviation. Using the PDT-3000 instrumented cartridge, the voltage on the surface of each drum inside a printer was sampled at 100 Hz while simulating the printing of a white page. The standard deviation of 300 consecutive data points was recorded.
8. Mean In-Situ Charge Discharge Voltage. Using the PDT-3000 instrumented cartridge, the voltage on the surface of each drum inside a printer was sampled at 100 Hz while simulating the printing of a gray page. The mean of 300 consecutive data points was recorded.

A life test experiment was conducted on two of the OPCs in the sample. These two OPCs were installed in printers which then printed 12,000 pages each, using the built-in continuous self-test mode of the printers. The preceding list of measurements were taken on each of these OPCs at 1,000 page intervals during the life test. Print samples using a specially designed test print were also printed at 1,000 page intervals for print quality analysis. These test prints were analyzed both visually and by means of the IAS-1000 automated image analysis system.

Results

Life Test Measurements

Figure 1 shows the relationship between the life test page count and the OPC coating thickness for the two recycled OPCs under life test up to 12,000 pages. The coating thickness decreases at a nearly constant rate throughout the life test. Figures 2-4 show the relationships between the life test page count and mean charge acceptance, minimum charge acceptance, and dark decay ratio, respectively, for the two OPCs under life test. All three of these measured parameters decrease steadily as the page count increases. These data suggest that the OPCs wear gradually, at a nearly constant rate.

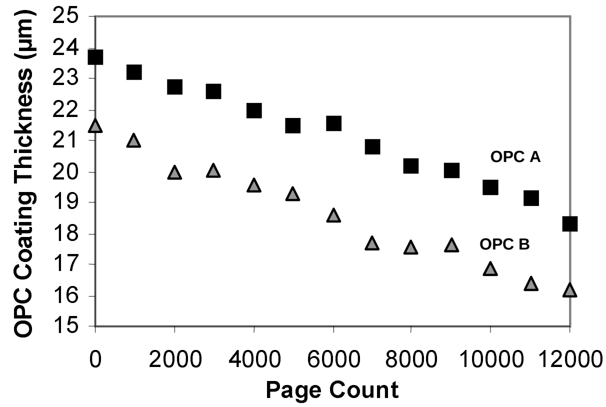

Figure 1 Decreasing OPC coating thickness due to repeated printing in life testing of two OPCs

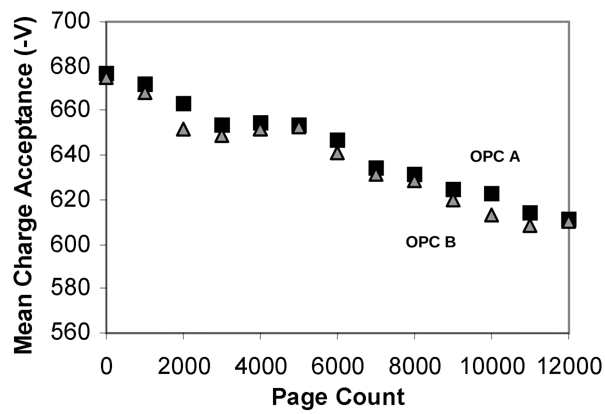

Figure 2 Decreasing mean charge acceptance due to repeated printing in life testing of two OPCs

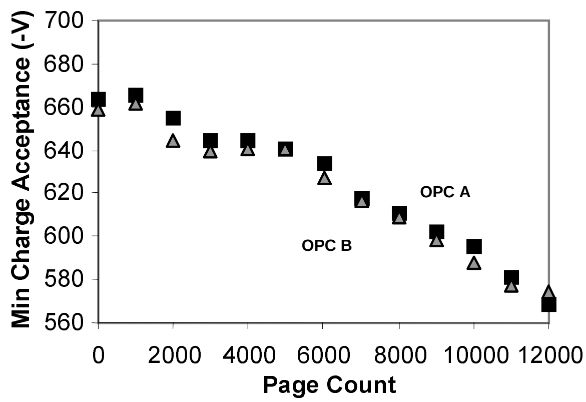

Figure 3 Decreasing minimum charge acceptance due to repeated printing in life testing of two OPCs

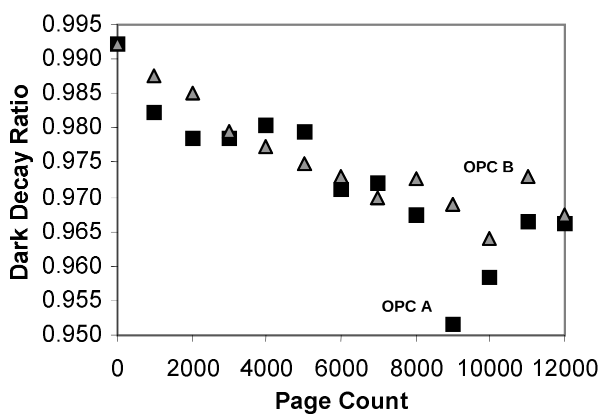

Figure 4 Decreasing dark decay ratio due to repeated printing in life testing of two OPCs.

PDT-2000LA Measurements on Used OPCs

Figure 5 shows the statistical distribution of the OPC thicknesses measured in this study. Note the distribution is approximately normal with a mean of 23 µm.

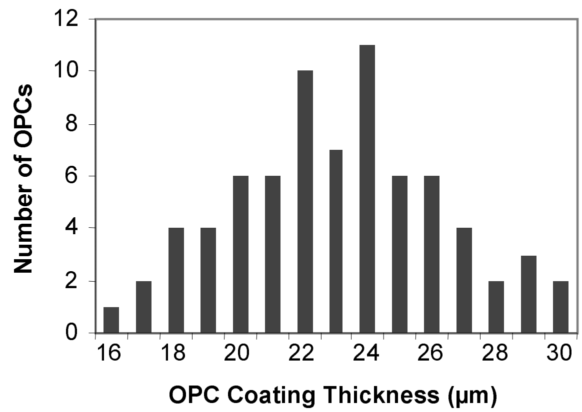

Figure 5 Histogram of measured OPC thicknesses in sample of 74 EX OPCs (70 used and 4 new).

Figure 6 shows the relationship between coating thickness and mean charge acceptance. The OPCs with thicker coatings produce higher charge acceptance measurements. The clear correlation suggests that mean charge acceptance is a good measure of OPC wear.

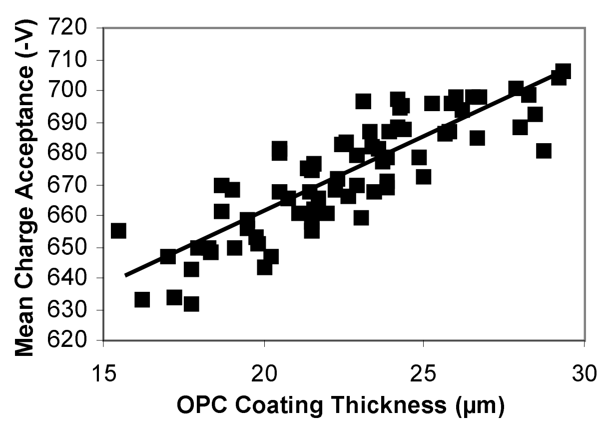

Figure 6 Relationship between coating thickness and mean charge acceptance in sample of 74 EX OPCs (70 used and 4 new).

Figure 7 shows the relationship between coating thickness and minimum charge acceptance. Note that although a correlation exists (minimum charge acceptance decreases with increased OPC usage), there are several outliers. These outliers correspond to OPCs which have local weaknesses, so that their average charge acceptance is much higher than their minimum charge acceptance, measured at the OPC's weakest point.

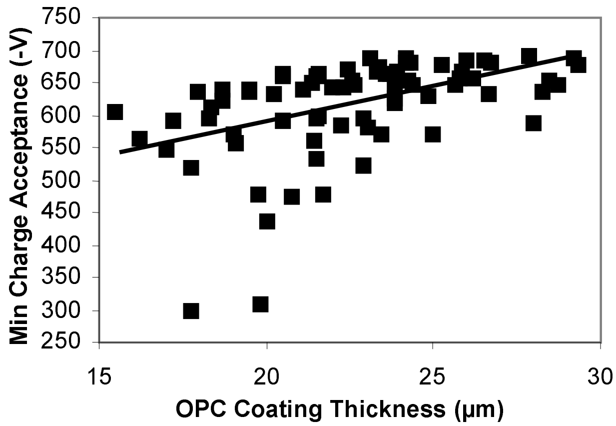

Figure 7 Relationship between coating thickness and minimum charge acceptance in sample of 74 EX OPCs (70 used and 4 new).

Figure 8 shows the relationship between coating thickness and mean discharge voltage. The OPCs with thicker coatings produce lower discharge voltage measurements. Note that this is opposite to the relationship observed for mean charge acceptance. Thus, the contrast potential between exposed and unexposed areas of a worn OPC is much less than the contrast potential for an unworn OPC. The clear correlation of Figure 8 suggests that mean discharge voltage, similar to the mean acceptance voltage, is also a good measure of OPC wear.

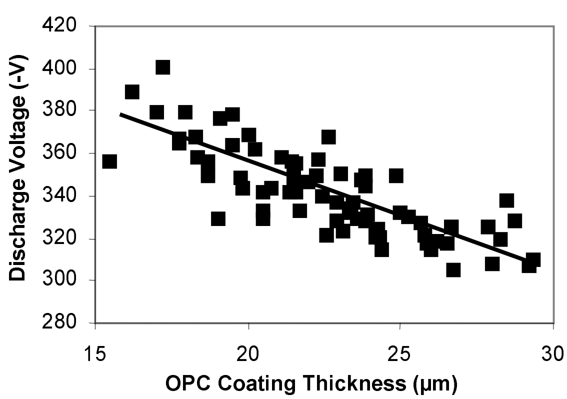

Figure 8 Relationship between coating thickness and discharge voltage in sample of 74 EX OPCs (70 used and 4 new).

The relationship between coating thickness and dark decay ratio is shown in Figure 9. Note the similarity to Figure 7 in that a correlation exists (dark decay ratio decreases with increased OPC usage), but once again there are several outliers.

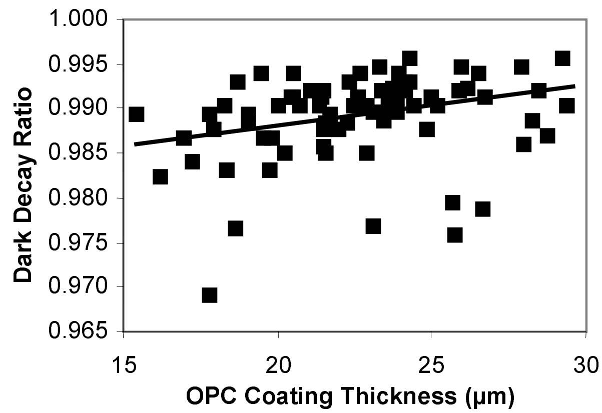

Figure 9 Relationship between coating thickness and dark decay ratio in sample of 74 EX OPCs (70 used and 4 new).

Discussion

Life Test Measurements

As previously discussed, print test evaluation is not a reliable predictive tool for OPC quality assessment. In this study, no systematic correlation was found between print quality measures (gray scale, resolution, and background) and the page count.

A good predictive measurement must be sensitive to OPC usage (wear). Although the print quality observed in print testing was nearly constant for the OPCs under life test, the coating thickness measurements (see Figure 1) show that the OPCs indeed wear continuously at a nearly constant rate. Unlike the print test measurements, the measurements made with the PDT-2000LA (see Figures 2-4) are directly related to the OPC usage.

Development of a Screening Methodology

As is the case in the remanufacturing practice, we do not know the detailed usage history of each of the recycled OPCs in our study. The coating thickness measurements reveal that the new OPCs have a coating thickness of about 29 µm. We assume that all the OPCs had nearly the same coating thickness when new, and that the coating wears continuously with use. This behavior is confirmed by the life test (see Figure 1). Therefore, we will use coating thickness as an indication of OPC usage (the most-used OPCs have the least remaining coating thickness).

How can the data reported above be used to distinguish the reusable OPCs from the others? Reviewing the data in Figure 6, we see that mean charge acceptance is directly related to OPC usage. Therefore, we can simply choose a threshold charge acceptance and reject all OPCs with charge acceptances below our threshold. In this way, we will reject the badly worn OPCs. In fact, the same approach could be applied to discharge voltages (see Figure 8). But since the discharge voltage measurement yields essentially the same information as the charge acceptance measurement, it is probably unnecessary to perform both measurements when screening this type of OPC.

A more conservative approach is to use the minimum charge acceptance measurement, and reject all OPCs which measure below a certain threshold. This would likely result in the rejection of all the OPCs which produced the outlying data points in Figure 7. It is significant that there are no outliers with minimum charge acceptance greater than the general trend (above the line). This reinforces the conclusion that the outliers correspond to OPCs with local defects, and therefore should be rejected.

The same argument applies to the dark decay measurements. If we reject all OPCs with a dark decay ratio below a certain threshold, we will reject the OPCs which produced the outlying data points in Figure 9. It is interesting to note that some of the same OPCs which produced the outliers in dark decay measurements (Figure 9) produced some of the best charge acceptance measurements. Clearly, the dark decay measurement reveals an OPC characteristic that does not affect charge acceptance.

Ultimately, the best screening approach relies on a combination of measurements. To be conservative, we reject all OPCs with a mean charge acceptance below a certain threshold, **and** we reject all OPCs with a minimum charge acceptance below a certain threshold, **and** we reject all OPCs with a dark decay ratio below a certain threshold. The OPCs which are not rejected are deemed reusable.

Establishing Accept or Reject Criteria

The methodology described above requires a threshold for each of the measurements; OPCs are rejected if any of their measurements are below the corresponding threshold. The establishment of these thresholds is based on both economic and technical considerations. Obviously, higher thresholds will yield higher quality cartridges with better reliability; a conservative choice. But if the thresholds are set too high, many useful OPCs may be wasted.

A practical approach is to use the test data to guide the initial selection of thresholds. The validity of the thresholds must be verified experimentally. For the OPCs tested in this study, we initially choose a mean charge acceptance threshold of 665 volts. This is only 5% below the nominal charge acceptance for new OPCs of 700 volts. Using this threshold, slightly less than half of the 70 used OPCs in this study are rejected.

Next, we review the minimum charge acceptance data of Figure 7. It is reasonable to choose a threshold which rejects the outliers of this graph, as well as the OPCs rejected by the mean charge acceptance criterion. In this case, a threshold of 620 volts is selected.

Finally, we select a dark decay ratio threshold which rejects the outliers of Figure 9. For the OPCs in this study, a threshold of 0.985 is selected.

Verifying the Accept or Reject Criteria

In preliminary field testing, the selected criteria were used for EX OPCs, and 17 recycled cartridges (with recycled used OPCs which were **not** rejected) were tracked after delivery to end-users. All 17 cartridges successfully completed an additional cycle of use. This result reinforces the merit of reusing recycled OPCs, and suggests that the selected accept/reject criteria thresholds are not too low. To further verify these criteria, the life tests (see Figures 2-4) were performed on used OPCs which were near the rejection thresholds. Both of these OPCs produced acceptable prints for an additional 12,000 pages! This outcome provides more support for reusing OPCs, and further verifies that our accept/reject criteria is sufficiently conservative.

Using these criteria, we find that almost 50% of the used OPCs in this study are reusable! The criteria can be refined with further testing, potentially resulting in an even higher yield. It must be emphasized that since these criteria are determined based on historical data for one particular OPC type (HP/Canon EX), their use must be limited to drums of the same type. The same methodology can be applied to other types of OPCs to establish accept/reject criteria for various OPC types.

Summary of the Recycled OPC Screening Methodology

A crucial assumption underlying the methodology in this study is that the OPC in consideration is a stable design (i.e. all OPCs of said design have similar performance), and that available historical data is representative of the typical OPC behavior. Given this assumption, the following procedure is used:

1. Establish a correlation between mean charge acceptance and OPC coating thickness. A well-behaved relationship suggests that mean charge acceptance is a good life predictor. Generally, both mean charge acceptance and minimum charge acceptance should be used in OPC screening.
2. Establish similar correlations for sensitivity (discharge voltage) and dark decay. Decide if any of these parameters can or should be used as independent predictors.
3. Use all predictors in combination.
4. Establish accept/reject thresholds based on economic considerations, desired quality level, and laboratory and field tests.

This method is useful for estimating the remaining life of a recycled OPC if the degradation mechanism is gradual wear (physical) or gradual degradation in electrophotographic properties such as charge acceptance, discharge sensitivity, and dark decay. This method is not suitable for detecting localized defects such as pinholes. The most commonly used methods in practice for pinhole detection are visual inspection and print testing.

Application of the Methodology to OPC Development

In this study, we have focused on the application of screening recycled OPCs to determine reusability. However, the same methodology can be applied to evaluate the quality of new drums in a production facility. Similarly, the techniques described can be used to assess experimental OPCs in a research and development setting.

Conclusions

1. Screening of recycled OPCs can be accomplished using a collection of scanner measurements, which unlike print test results, are sensitive to gradual changes in OPCs. Specific measurements include: mean charge acceptance, minimum charge acceptance, discharge voltage, and dark decay ratio.
2. Accept or reject criteria can be established based on economic considerations, acceptable quality level, and historical data.
3. In-situ measurements by the instrumented cartridge method, together with life tests and field tests should be conducted to verify the validity of the chosen parameters and the corresponding criteria.
4. For the HP/Canon EX drum sample studied, almost 50% of the recycled drums are reusable!

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