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Interactive Use of a Time-shared Process Control Computer in Electrophotographic Sensitometry

Abstract: The usefulness of electrophotographic exposure sensitometry as a means of characterizing and evaluating new photoconductor materials has been extended by coupling the experiment to an on-line computer. This automated system provides several new functional capabilities not realistically attainable in manual operation and drastically reduces the time lag in the exchange of information between research workers who prepare materials and those who evaluate the materials. These various improvements have been achieved by extensive use of interactive graphic techniques and a user-oriented data-base organization.

Introduction

Since the advent of photoconductors in electrophotographic copying processes, a variety of measurements have been devised to aid in characterizing and evaluating the relevant physical properties of these materials [1-3]. One such measurement, exposure sensitometry [4], has proved particularly useful. This measurement technique is significant because its results can be related to fundamental material properties [5-7], e.g., carrier photoinjection efficiencies; moreover, the sensitometry experiment closely approximates several aspects of machine and device operating conditions for the photoreceptor.

This paper describes the use of a time-shared process control computer to augment, in a significant way, the utility of sensitometry measurements. In addition to the advantages gained in quantity, quality, and reproducibility of the data collected, the use of the computer provides an enhanced functional capability that could not realistically be achieved with manual operation. This advantage is especially true for the rapid comparison of many measurements in a number of physically meaningful formats. The improved performance has been accomplished by operating the experiment in a mode that involves much interaction between the operator and the computer, especially during data analysis. Graphic displays are also used extensively.

The sections that follow outline the essentials of typical sensitometry experiments and discuss the approach used in coupling such instrumentation to an on-line computer. The major advantages relate mainly to the availability of on-line analysis for this type of data rather than to the improvements associated with data acquisition. An illustrative example, showing the types of information that can be recovered interactively from this system immediately upon completion of an experiment, is discussed in detail.

Electrophotographic sensitometry

The process steps in electrophotography are well known [8]. The first two of these steps result in the formation of the latent electrostatic image on the photoreceptor, and the sensitometry work reported here pertains to this initial part of the copying process. The initial steps are 1) sensitization of the photoreceptor by depositing a charge on its surface in the dark and 2) exposure of the sensitized photoreceptor to the light image such that partial or complete decay of the surface charge occurs in the light areas of the image. The remainder of the copying process involves development of the latent image and transferring it to paper. These processes are not discussed here.

Sensitometry, as the term is used in this paper, refers to precise measurements of the surface potential of a photoconductor under a variety of well-defined charging and exposure conditions. Numerous types of information can be derived from such measurements, and the reader is referred elsewhere [9] for a description of the various experimental modes that are often used. In this paper we describe, by way of specific example, only those aspects of sensitometry necessary to illustrate the enhancement afforded by coupling such instruments to an on-line computer and utilizing interactive graphics. The extension of the examples to other cases of specific interest is straightforward.

The features of a typical sensitometer are illustrated in Fig. 1. The hardware shown includes a rotating cylindrical drum that moves at a nominally constant angular velocity. It carries one or more samples past stationary devices situated near the outer rim of the drum. The test samples consist of thin layers of photoreceptors. Speeds generally encountered are in the range 10 to 50 cm/s (4 to 20 in./s), as measured at the circumference of the drums, for which the diameters range from 18 to 53 cm (7 to 21 in.). The representative process depicted in Fig. 1 may be thought of as proceeding counterclockwise from the charging corona at the upper right, past the light-source exposure station, and subsequently through restoration procedures at the lower right. The information desired is the surface potential of the sample at various times during the test. These potentials are detected with capacitively coupled electrometer probes placed near the drum at appropriate stationary points; e.g., electrometer E1 measures the sample potential in the dark immediately after charging and E2 measures the sample potential after exposure. Potentials normally encountered in such measurements lie between 0 and ±1000 V. The electrometer positions may be altered occasionally but they remain fixed throughout a given test procedure. During measurement, the drum is free running through a number of revolutions while data from the electrometers are registered on a multichannel chart recorder. An idealized data stream is shown schematically at the bottom of Fig. 1, with a more detailed representation in Fig. 2. As each sample passes beneath an electrometer probe, a voltage profile is recorded, its height being proportional to the surface potential of the sample. The surface of the drum between samples is held at ground potential to provide a zero reference signal in the background.

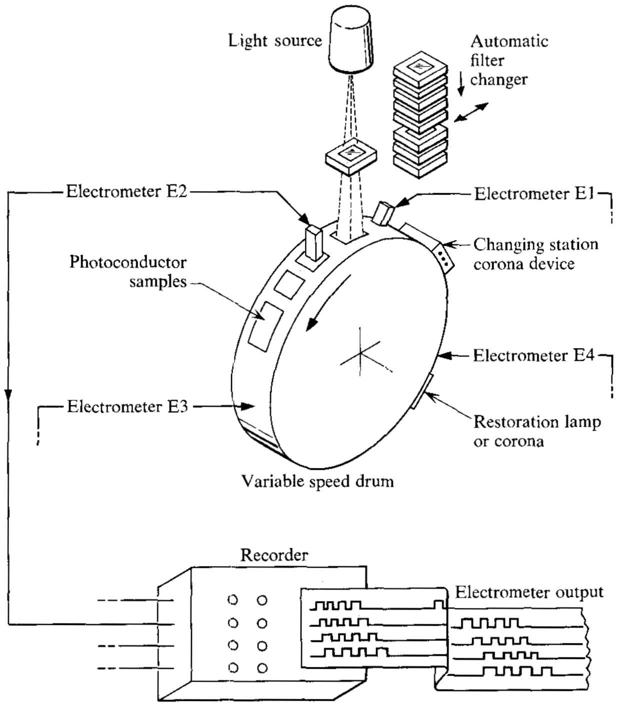

Figure 1 Experimental apparatus for exposure sensitometry.

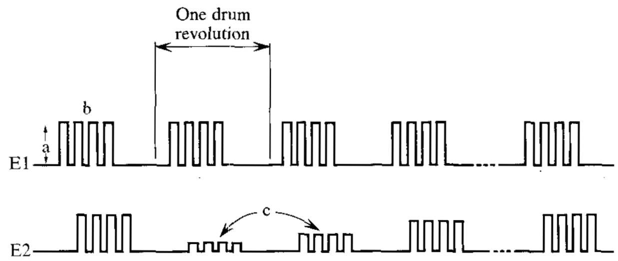

Figure 2 Schematic representation of typical data streams recorded by electrometers. (a) Potential on charged sample, (b) four samples, (c) the variation of exposure that causes potentials to vary between drum revolutions.

In most cases, the useful output of such an experiment involves a plot of certain surface potentials of a sample as a function of some externally varied stimulus. Of the many test configurations used, one of the most important is that in which the voltage decay at the photoconductor surface is observed as a function of the illumination exposure energy. This technique is referred to as *exposure sensitometry* and the results of the measurement are generally plotted as the sensitometric characteristic curves for the photoconductor, as illustrated in Fig. 3. The lower portion of the figure illustrates schematically how such results are obtained from the original data stream. The S-shaped curve labeled E2 is a plot of the surface potential, after exposure, vs the logarithm of the exposure energy. The logarithmic scale is chosen to permit extension of the curve over the entire range of exposure energies significant in electrophotographic copying of documents. For all practical purposes, zero exposure energy simply corresponds to moving suffi-

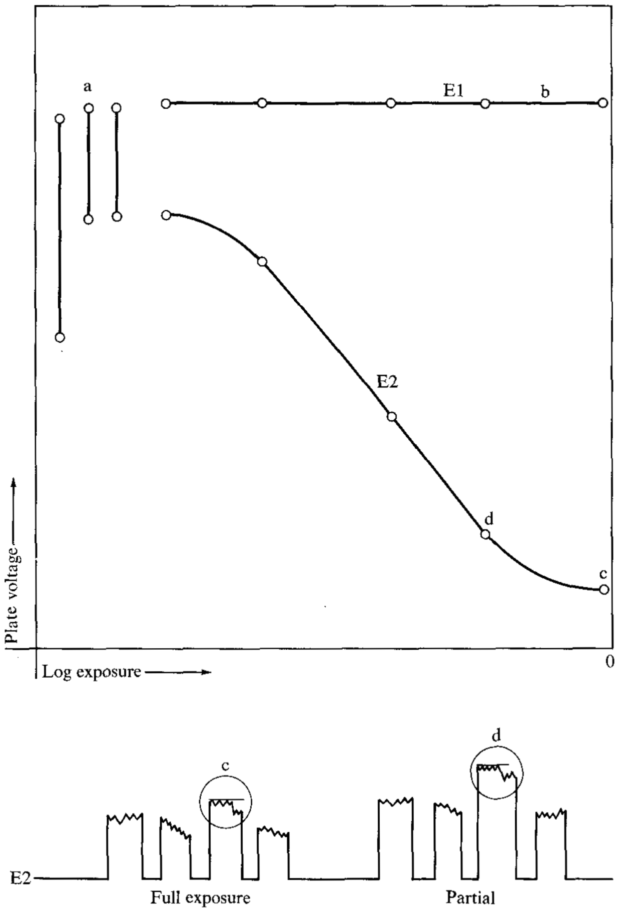

Figure 3 Generation of sensitometric characteristic curves from recorded potential profiles. (a) Dark decay curves, (b) initial charge; point (c) represents full exposure and (d), partial exposure.

ciently far to the left on this scale so that the surface potential is dark-decay limited. The exposure energy during a test is varied between drum revolutions by attenuating the full exposure energy (plotted at the far right on the abscissa) with a series of neutral density filters, as depicted in Fig. 1. In Fig. 3, the curve marked E1 plots the dark voltage preceding each exposure cycle. The abscissa values have no significance for the E1 curve except to indicate the point in the partial exposure test sequence at which these data were taken. The three vertical lines at the left of the characteristic curves are (from right to left) indications of the voltage decay of the sample in the dark from electrometer E1 to electrometer E2 at the beginning and end of the test, and of the dark decay during an entire drum revolution.

The above set of reduced results has been described to familiarize the reader with one example of the type of data reduction required in the sensitometric experiments. The characteristic curve set contains a wealth of information relevant to photoconductor performance in an electrophotographic machine under a variety of imaging conditions [8, 9]. The mathematics involved in the data reduction for one sample under one test is trivial. Similar tests, however, must normally be conducted for a large number of samples and in a large number of process configurations. Under such conditions the burden of data reduction imposes a significant time lag between the measurement and the evaluation of physically useful results. This delay hampers communication between the investigators responsible for photoconductor materials preparation and those responsible for materials characterization. The laboratory automation system described here not only reduces this "communications lag" but also provides more data of higher quality, more uniform data reduction, and improved methods of evaluating sensitometric information. The gains in the quantity, quality, and uniformity of the data are due to several factors. With the computer, resolution and the linearity are improved for both dependent and independent variables, as compared to conventional strip chart recording. Surface potential readings using 14-bit analog-to-digital conversion achieve a precision of better than one part in 10^4, and it is feasible to resolve spatial nonuniformities in a sample on a 2.54 mm (0.1 in.) scale at typical drum speeds. In addition, use of the computer to obtain curves through experimental points, to plot the curves, and to assist with record keeping reduces the human error normally encountered in handling large quantities of data. It is estimated that the overall cost per experiment in our particular case was reduced by a factor of two, and the number of completely analyzed results obtained increased by a factor of four. Although computer-assisted sensitometry as described here requires full time technical support from an operator, the activities of the operator tend to be creative, primarily involving observing and comparing results from many experiments, as opposed to generating numerical details from chart records and plotting graphs. For sensitometry conducted in a product test laboratory rather than a materials development laboratory, it is anticipated that the system described in the next section could be implemented with minor modification to nearly eliminate the need for the operator. In such a situation the flexibility afforded by use of the computer is important primarily when test procedures need to be altered.

Computer-assisted sensitometry

The requirements of sensitometric tests change frequently, because the number and size of the samples are always variable, the drum size varies with different sensitometers, and the drum speed, exposure levels, and electrometer positions are often altered to simulate a particular machine configuration or to evaluate a specific machine characteristic. This need for flexibility in the test configuration had a profound effect on the design of the automated system and led to the adoption and development of a highly interactive mode of operation, both in defining the details of the test before data acquisition and, especially, during subsequent data analysis. The computer used to assist the sensitometry work is an IBM 1800 Data Acquisition and Control System running under the Multiprogramming Executive (MPX) operating system. This machine is used entirely for laboratory automation at the San Jose Research Laboratory and provides a timer-based experimental monitor that allows simultaneous use for many slow experiments ($\leq$ 100 points per second) and a few fast experiments ($<$ 18,000 points per second). The interested reader is referred elsewhere [10, 11] for details on the system hardware and software configuration. The interfacing of the sensitometer to the computer was implemented using one process interrupt bit and one each of 16-bit digital input and digital output groups connected to switches and lamps at a remote operator console in the sensitometry laboratory. The use of such hardware to communicate experimental test parameter values and commands to the computer has been described previously [12]. In future implementations of this type of instrumentation, it would be desirable to incorporate more operator-oriented devices (thumbwheels, keyboards, character displays) that have become commercially available. The signal interface also required one analog input point for each electrometer and analog output to provide graphic display of raw data and analyzed results on a Tektronix 611 Storage Display in the laboratory console. For hard copy output, an IBM 1627 plotter at the computer and an IBM 1053 printer in the laboratory were used. A schematic overview of the system is shown in Fig. 4.

One challenge in the design of the software [13] to handle the collection and analysis of the sensitometry data involved problems inherent in organizing and manipulating the large quantities of data that are generated. It was necessary to devise schemes for compressing these data into physically useful results and to provide flexibility to the test operator for quickly retrieving desired information for comparison with past test data. This type of data manipulation problem has become somewhat commonplace in recent years for the extensive data base systems residing in large computers (e.g., IBM System/360 or System/370). However, it is relatively unusual in the context of an on-line, solid-state physics experimental environment with a medium size computer, especially if extensive interaction with the data through graphic display is also required [14]. The problem was approached by making extensive use of dynamic file space allocation routines [11], which allow a user to

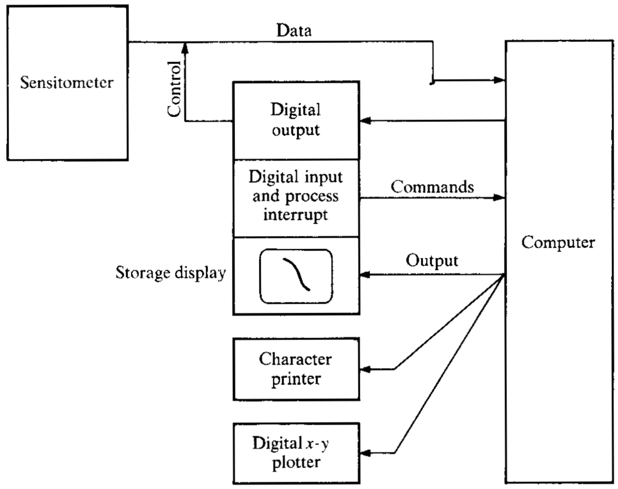

Figure 4 System diagram for computer-assisted sensitometry.

allocate, under program control, large amounts of disk storage from a common pool and to use that space for private files on a temporary basis. Availability of these dynamic file routines allowed the following key decisions to be made at an early stage in the software planning:

1. No rejection of background data would be performed during the test (i.e., no hardware rejection of signals below a certain level). To allow maximum flexibility for accommodating as yet unforeseen test configurations, all data would be sent to the computer in real time from all active electrometers without regard to the character of the data, in much the same manner as they would be sent to a strip chart recorder.
2. The programming to handle test definition, data acquisition, initial data compression, and final analysis was constructed in a modular fashion (i.e., consisting of many small programs rather than a few large ones) in order to facilitate interactive operation. A hierarchical scheme of on-line data retention was devised to allow both short-term retention of some voluminous data and longer retention of essential physical results.
3. Although graphic hard copy of the analyzed sensitometric results would be obtainable, if desired, within minutes after a test, provision was made for "production" plotting of a previous day's test results to be executed during the less busy nighttime hours, automatically and without operator intervention.

To provide a more explicit picture of how computer-assisted sensitometry operates within the foregoing framework, the example discussed here shows how to obtain characteristic curve information of the type illustrated in Fig. 3. It is helpful to separate this operation conceptually into six phases: test definition, data acquisi-

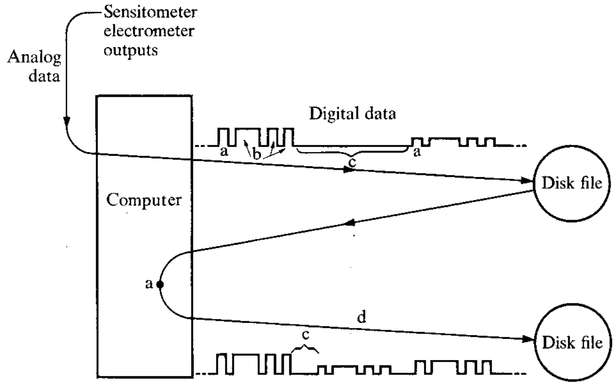

Figure 5 Preliminary data reduction task executed automatically on completion of data acquisition. (a) Locate leading edge of first sample on each drum revolution, note file address, calculate drum speeds, (b) calculate location of other samples using sample size table, (c) discard, (d) store data and note location with respect to electrometer drum revolution and sample.

tion, primitive analysis and data compression, screening of selected data for comparison and decision making, generation of characteristic curves and related performance parameters, and production plotting. The fourth and fifth of these phases involve extensive use of interactive graphics in an on-line experimental situation, and it is here that the computer has made its most significant impact on the sensitometry measurements. The plotting phase involves no particularly unusual concepts and is not discussed further.

• *Test definition*

Before a sensitometric test is run, values are entered into the computer for such key parameters as drum size, test speed and duration, the number, size, and positioning of the samples, etc. This information is entered through digital sense switches and can be displayed on the storage screen for purposes of convenient validity checking and updating. To relieve the operator of unnecessary calculations and excessive data entry, default values are often used for some parameters and others may be computed using internal algorithms and minimal data entries. In addition to the computation of these run-definition parameters, several data tables are constructed through interactive use of the laboratory console sense switches and the storage display to provide detailed information on the test configuration, e.g., the sequencing of partial and full exposures during the test and the magnitudes of the partial exposure energies. An additional function of the test initialization procedure is to have the 1800 use the test configuration parameters to compute and dynamically allocate the file space required during data collection. The space available for a single test is software limited to a maximum of 32 000 points for the data from each electrometer which, at a typical data rate of 100 points per second, permits data collection for somewhat longer than five minutes.

• *Data acquisition*

As indicated previously, the computer is used during data collection primarily as a high-resolution multichannel strip chart recorder, the experiment being run under the slow scanning mode of the general experimental monitor first described by Gladney [10] and later modified by Raimondi [11]. The computer provides control signals through two digital output bits to initiate the locally driven hardware required by the experiment, e.g., a filter insertion apparatus to vary exposure energies between drum revolutions. Aside from these initial control signals, the experiment is allowed to proceed to completion in a free-running mode. The synchronism between the test operations in the laboratory and the data acquisition by the computer can be monitored by the operator, since the 1800 displays and updates the current drum revolution count on the interface console. In accord with the protocol of the experimental monitor program, the collected raw data are written into the allocated disk files automatically. Typical test configurations involve approximately 20 drum revolutions and about two minutes running time.

• *Primitive data analysis and compression*

Figure 1 indicates that the data streams from the electrometers generally include sizable regions of the background signal. This is especially true when only a fraction of the drum surface contains some samples. In addition, the raw data collected during a test are not in the most useful format for subsequent operator accessing, making comparisons, and generating the desired results. A set of algorithms was developed [13] that was sufficiently general to accomplish preliminary analysis on the raw data, eliminate unwanted background regions, and reorganize the data into smaller files having a highly functional format. These algorithms are executed immediately after data collection and are totally independent of the test configuration. Several key tasks are accomplished during this analysis, and all subsequent data handling routines depend critically on these preliminary computations.

A summary of the procedures involved in this first analysis is illustrated in Fig. 5. First, the entire data stream of the leading electrometer (E1 in Fig. 1) is screened with a step-finding algorithm to locate the leading edges of the voltage profiles from the first sample, which serve as fiduciary marks in the data file, one mark for each drum revolution. These reference points are

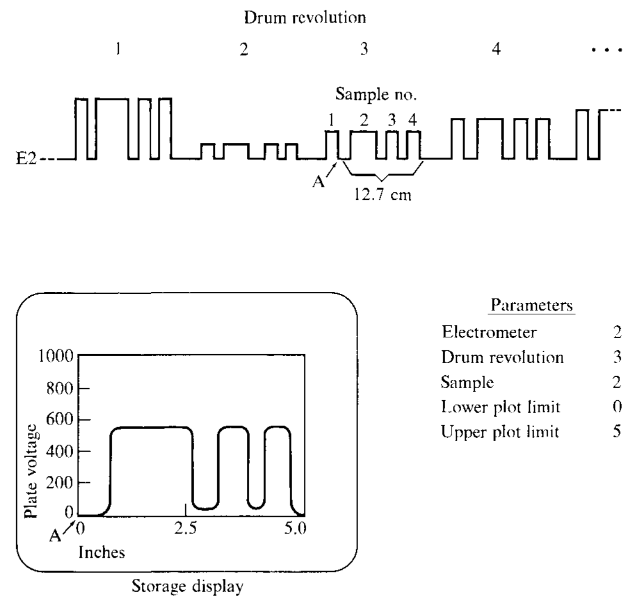

Figure 6 Parameter-controlled retrieval and display of voltage profiles.

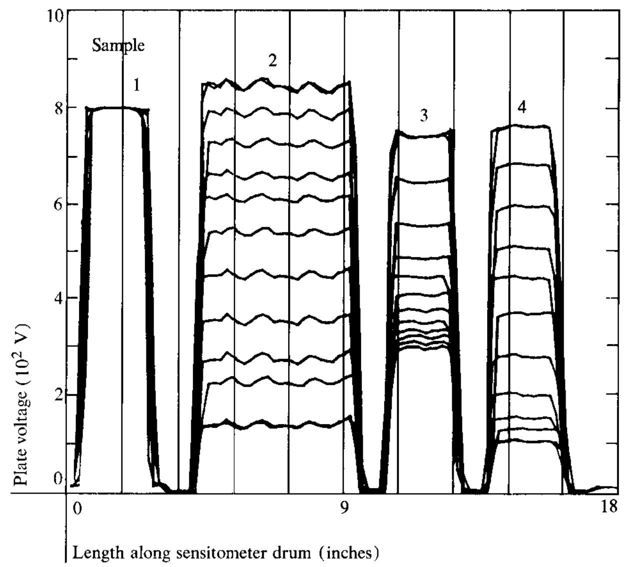

Figure 7 Display overlay of voltage profiles from four photoconductor samples for all exposures encountered during a test.

then used to compute the drum's average speed during *each revolution* of the test, which is necessary because one-percent deviations in sensitometer drum speed due to random line voltage variations are not uncommon. The computed speeds are used subsequently as a fine adjustment to bring into synchronism the overlaid display data from different revolutions. Once these revolution reference points and drum speeds have been calculated, a set of secondary references is computed to determine the relative displacements in the data file of the data region from each individual sample. At this point unwanted background regions are discarded. This procedure is then repeated for the data stream(s) from any additional electrometer(s) active during the test. In cases where one or more of the electrometers has been repositioned since the previous test, the algorithm makes use of the raw data streams and computed drum speeds to determine the new relative electrometer positions. The final task of the preliminary data reduction is the transfer of the test data to newly allocated files (one for each electrometer) in which the data organization is governed by the revolution and sample reference points just calculated. At this stage the larger files used during data acquisition are released to the dynamic file pool. The execution of all the tasks just described is usually completed within 60 seconds after the end of data acquisition, and during their execution statistical information derived from the data is displayed to the operator.

The essential aspect of these data reduction processes is the compression of raw data (perhaps more than 100 000 points) and the rapid organization of that data into a scheme whereby any desired information from the test can be selectively accessed by the operator in the laboratory. The organizational scheme can be viewed simply as the filing of each physically meaningful unit of data in its own compartment in a three-dimensional coordinate space. They physical unit of data is the voltage profile recorded by a single electrometer from one sample during a given drum revolution. Any location in the coordinate space is specified by three integers: an electrometer number, revolution number, and sample number, and the desired data can be accessed by using simple algebraic expressions that translate these integers into appropriate addresses in the reduced data files. In systems terminology, this scheme corresponds to describing a large data base with user-oriented rather than system-oriented qualifiers.

• *Screening selected data*

With the data categorized logically by electrometer, drum revolution, and sample, it is straightforward to retrieve desired portions of the test results for examination by the operator. For this purpose the storage display is used to plot the data (sample voltage vs distance along the sensitometer drum) with parameters entered through the sense switches that govern specifically the data being plotted. An example of this information retrieval and display process is schematically illustrated in Fig. 6, where the data recorded by electrometer E2 during the third drum revolution are displayed, starting with the second sample. By varying the parameters called lower and upper plot limit, the operator specifies the extent of

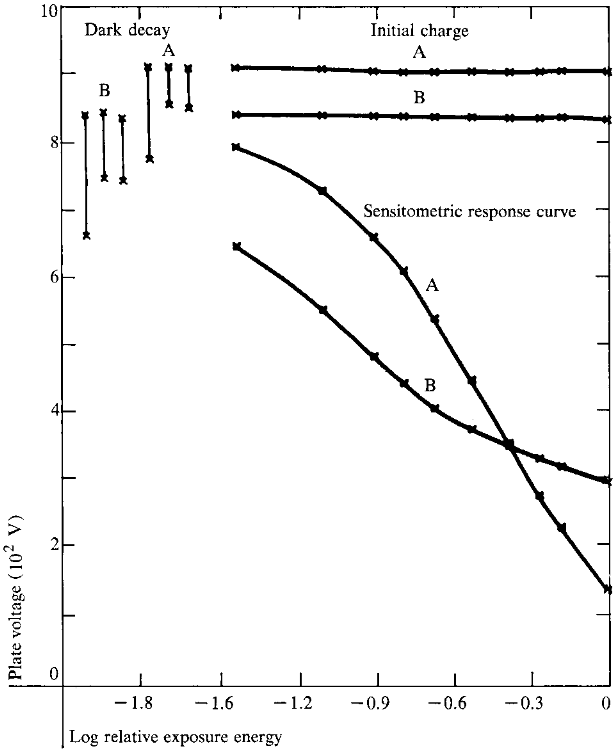

Figure 8 Display overlay of computer generated characteristic curves for two photoconductors A and B under the same test configuration.

the data (in units of projected distance along the sensitometer drum surface) to be viewed. This feature permits, in the one extreme, "wide angle" viewing of all the profiles recorded during a test and, in the other extreme, "microscopic" observations of highly detailed information from a small region of a single sample. Sufficient flexibility is provided for any intermediate situation, e.g., viewing all data from one or more samples overlaid from all the drum revolutions, or perhaps including only certain drum revolutions or certain samples.

An illustration of actual data, as displayed on the storage screen, is shown in Fig. 7. The vertical grid lines are plotted on the screen to aid the operator in identifying, to the computer, sample regions of particular interest. In the overlay of Fig. 7, a ready comparison can be made of the voltage decay behavior of four different samples during a complete exposure sensitometry test. The samples vary considerably in their responsiveness to the different illumination levels that are used during different drum revolutions. For each sample, the progression of voltage profiles from top to bottom indicates the potential reached, after charging and exposure to progressively increasing energy. The first sample shows no response, the second and fourth samples exhibit responses that vary reasonably uniformly with exposure energy, and the third sample is very sensitive at small exposure energies but retains a high residual voltage at the larger exposures. Such differences in sensitometric behavior lead to significant differences in the electrophotographic performance obtainable from the photoconductors in a process configuration. The computer assisted sensitometric experiment permits an immediate scan and comparison of details of test data in a highly organized fashion. The technique thus allows observation of interesting phenomena that would otherwise go unrecognized and it thereby provides a tool for correlating such phenomena with the photoconductor preparation techniques.

- *Characteristic curves*

The characteristic curves of each sample are of primary interest in exposure sensitometry. These curves are obtainable directly from data of the type shown in Fig. 7, as long as the exposure energy associated with each voltage profile (i.e., with each drum revolution) is known. In the computer-assisted sensitometry discussed here, these energies are interactively entered into the computer by construction of a table at the laboratory console. Sense switch data are entered and the storage screen is revised. A more elegant method envisioned as part of future sensitometer improvements would incorporate online computer recording of the exposure energies during the test by means of signals from calibrated photon detectors.

One of the problems encountered in the adequate definition of a characteristic curve from sensitometric data is that frequently a smooth curve must be constructed through a relatively small number of experimental points. The computer can utilize a deterministic algorithm to reproducibly generate a well-defined curve through the observed data points. The algorithm chosen for this purpose was that for a natural cubic spline, which assures continuity in the function generated and in its first and second derivatives, and also permits construction of a curve exactly through the experimental points. Where physical models are available to describe the exposure sensitometry of the photoconductor, one may also use the computer for least squares fitting of a predicted curve to the recorded data, thereby deriving values for the parameters of the model [4, 7].

Generation and display of characteristic curves can be accomplished within seconds after scanning the test data. Furthermore, curves can be routinely generated for a particularly interesting, and perhaps anomalous, small region of a sample. Focusing attention on exceptional phenomena in this manner helps the photoconductor materials scientist to understand and exploit novel properties.

Typical computer-drawn characteristic curves generated for two different samples during the same test procedure are illustrated in Fig. 8. The S-shaped curves are computed as described earlier and contain information of ultimate relevance to copy speed, grey-scale resolution, ghosting, and a variety of other factors important in electrophotography [8, 9]. The actual data points from which the smooth curves are generated are marked by ×'s. The label spaces on both axes are used to display pertinent information regarding the test, whereas the actual plotting units correspond to voltage on the ordinate and the logarithm of relative exposure energy (i.e., negative neutral density values) on the abscissa. The abscissa scale is chosen so that each tick mark represents a change in exposure by a factor of two, i.e., one *f*-stop. Where hard copy output is desired, duplicates of the characteristic curves are drawn on the paper plotter. In addition, selected numerical results obtained from an analysis of the characteristic curves are printed on the laboratory typewriter. As noted earlier, voluminous amounts of plotting may be automatically deferred until the late night hours.

One of the advantages of on-line computer generation of these curves is the ability to rapidly compare, by means of overlay on the display screen, analyzed test results for different samples, process configurations, ambient environmental conditions, etc., as a function of repetitive cycling. In order to facilitate comparison with data recorded at an earlier time, provision was made (using the dynamic file routines) to retain on-line up to eight compressed raw data files of potential profiles and up to 100 sets of characteristic curve results. The limits on data retention in both cases are a function of available disk space on our system and are not intrinsic to the software design. An example of on-line data comparison is seen in Fig. 8. One observes markedly different behavior in such properties of the photoconductors as charge acceptance, dark decay, region of maximum sensitivity (derived from the slope of the characteristic curve), absolute sensitivity (derived from the position of the curve on the exposure axis), and residual voltage under maximum available illumination. Because of the ability to make such comparisons in essentially real time, the overall information feedback period between materials preparation and evaluation efforts has been reduced from one week to less than a day.

Present limitations

It is appropriate to comment on the most significant limitations of the computer-assisted sensitometry system described here. These can be categorized generally as limitations of space and of data sampling rate. The critical space restriction arises because of the limits imposed by our system on the amount of compressed raw data that can be retained. At present this limit has been set at eight electrometer data streams, independently of whether the data were gathered during one or several experiments. This situation forces the operator to make decisions regarding further analysis of the data at quite an early stage, in order to make room for subsequent data. This restriction could be alleviated by increasing the available direct access file space on the computer.

The second significant limitation mentioned involves the upper limit of 100 samplings per second for an analog input line imposed by our slow-scanning laboratory automation time sharing monitor. This has several consequences. First, at typical drum speeds presently in use, one can resolve only sample nonuniformities on the order of 0.25 cm (0.1 in.) and thus it is not practical to work with samples smaller than about 2.5 cm in length. These limitations become more restrictive as speeds increase, which is a clear trend for the future in sensitometry. In addition, the limited data sampling rate makes it difficult to achieve accurate registration of overlay displays for experiments in which the drum speed is not uniform, despite the computation made for average velocity during each revolution. This problem is worsened occasionally by the occurrence of 1 to 2 millisecond jitter in the data sampling periods when the computer time sharing system is under heavy load from other experiments. A solution that suggests itself for the sampling rate problem is to convert the experiments to the fast scan mode of our monitor, which runs independently of the slow scanning system and collects data at up to 18 000 points per second. This mode of operation has been implemented successfully with several other experiments on our system.

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13. Specific programming code is not available, but a schematic flow-chart-like representation of a number of the important routines is included in Fig. 5.
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