Digital Reconstruction of Faded Color Photographs

Rudolf GSCHWIND and Franziska FREY

Abstract.

Photographic three-color materials possess a poor stability when exposed to light, chemicals, heat and humidity. As a consequence the color of photographs deteriorates with time. Because of the irreversibility of the processes causing the dyes to fade, it is impossible to restore the images by chemical means.

Digital imaging is a powerful tool for the reconstruction of faded color photographs [1–12]. To achieve good results, scanning methods must be based on photographic, not on colorimetric fundamentals. The reconstruction algorithm used is derived from statistical and chemical investigations on the bleaching behavior of photographic color materials [13–16] and on spectrophotometric analysis of old, bleached color materials.

Résumé.   Les documents photographiques en couleurs résistent mal à la lumière, la chaleur et l'humidité. En conséquence, la couleur de ces photographies se détériore avec le temps. Du fait de l'irréversibilité des réactions qui provoquent le délavement des pigments, il est impossible de restaurer les images par des moyens chimiques. L'imagerie digitale est un outil puissant pour la reconstitution de photographies couleurs pâlies [1–12]. Pour obtenir de bons résultats, les méthodes de scannage doivent être basées sur des principes photographiques et non colorimétriques. L'algorithme de reconstitution est basé sur des analyses statistiques et chimiques du vieillissement de documents photographiques en couleurs [13–16] et sur une analyse spectrophotométrique de photographies couleurs anciennes et pâlies.

Keywords: Art photography, restoration of color materials, digitalization, spectrophotometric analysis.

Mots-clés : Photographie d'art, restauration d'images photographiques, numérisation, analyse spectrophotométrique.

✉ Rudolf GSCHWIND; University of Basel; Institute of Physical Chemistry; Scientific Photography Lab; Klingelbergstraße 80; CH–4056 Basel (Switzerland).
Fax: +41 61 267 38 55   E-mail: gschwind@foto.chemie.unibas.ch

✉ Franziska FREY; Image Permanence Institute; Rochester Institute of Technology; 70, Lomb Memorial Drive; Rochester, NY 14623 (U.S.A.).
Fax: +1 716 475 58 04

1. Introduction

Until now, archives of photographs in museums have been used principally for the documentation of research and collections. But more and more old photographs become collector's items themselves. Their unique importance for research relating to the history of civilization is due to the fact that they are the only authentic sources for certain subjects or periods of time. However in most case the storage conditions of the pictures are unsuitable, and a lot of them are in a poor state, because photographic film and paper are unstable media.

Color photographs show the worst degradation behavior. The dyes of common chromogenic processes are chemically rather unstable. Both the thermodynamic and the photochemical stability are low and the expected life span of color material is in the order of years to decades. Improper processing or environmental influences such as light, chemical agents, heat, humidity and storage conditions, affect images by bleaching the dyes or producing stain. Photographic films contain not only dyes but also a few other components (sensitizers, color couplers, stabilizers etc.) which can alter with time.

Excluding humidity helps to prevent bleaching to a certain extent but the only reliable method to keep color photographs for a long time is dark storage at low temperature and low humidity [17–23]. In case the storage conditions were not ideal and the photographs are bleached, the question of restoration becomes evident. Restoration of bleached color materials by chemicals, as is practical principally in black-and-white (b/w) photography, is impossible, because the bleaching of dyes is an irreversible process.

Until now restoration has been performed by photographic copying, but this method is slow, needs skilled photographers, and works only if the bleaching process has not proceeded too far [24–26]. Fourier-optical methods have also been proposed [26].

We therefore attempt to reconstruct faded color photographs by digital image processing. It is important to be aware of the fact that digital reconstruction is not a restoration in the classical sense. For b/w photographs restoration and conservation of the photograph usually takes place on the original support, but in the case of color photographs such a restoration of the original is not possible. The aim of the reconstruction is to restore the appearance of the original colors as accurately as possible on a new material (with the help of a mathematical model) and not the restoration of the original dyes.

The digital method is quick and inexpensive, and it does not affect the original photograph. Moreover it is a very universal method. As an additional advantage, the photograph remains in digital form in the computer, ready to be used in a data-base system. Recent tests also showed promising results in the reconstruction of color movie films. Figure 1 demonstrates some examples of the digital reconstruction process.

Fig. 1.– Examples from the actual research

The photographs shown are a work of the american artist *Bruce Naumann*. After seeing a Man Ray retrospective at the Los Angeles County Museum of Art in 1966, he made a group of eleven photographs. These photographs were taken 1966/1967 and reprinted and sold as a portfolio edition in 1970. The photographs were printed probably on *Kodak Ektacolor Paper* in the format of about 50 × 60 cm, mounted on foam sheets and exhibited under glass. One of the collection *Eleven Color Photographs* is in the swiss museum *Hallen für Neue Kunst, Schaffhausen*.[1] These photographs were exhibited without any special precautions (light protection) during several years. After the exhibition "Bruce Naumann" 1994 at the Walker Art Center in Minneapolis[2] it was evident, that the photographs in the Hallen für Neue Kunst had undergone strong bleaching. They show the typical light-bleaching aspect, *i.e.*, some staining and a destruction of the magenta colorant and hence, a greenish coloration. It is interesting to note, that the degree of bleaching is quite different for the different photographs. The photographs, together with gray- and color wedges, were digitized using a Kontron ProgRes 3012 CCD camera, equipped with 2 mm thick interference filters. Lighting was done with HMI lamps.

On the left hand side you can find the original (faded) photograph and on the right hand side the digitally reconstructed version.

---

[1] Hallen für Neue Kunst, Baumgartenstraße 23, CH–8200 Schaffhausen (Switzerland). Curator: A. A. Ritter.

[2] *Bruce Nauman* (Ed. Joan Simon, ISBN 0-935640-42-8). The exhibition "Bruce Naumann" was organized by Kathy Halbreich and Neil Benezra, Walker Art Center, Minneapolis, April 1994.
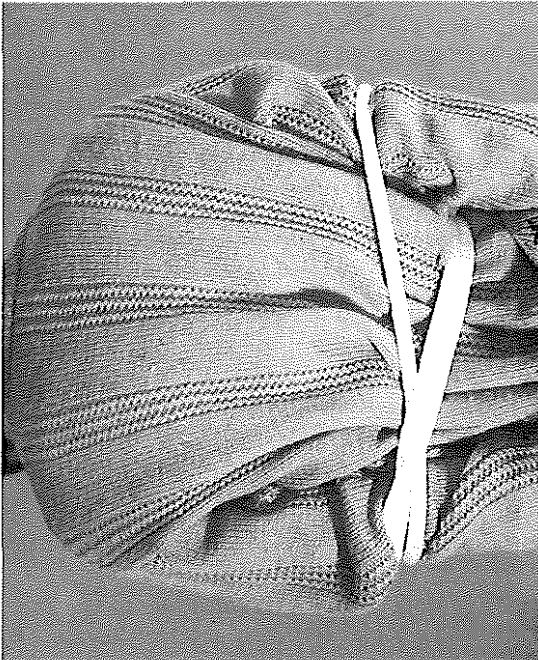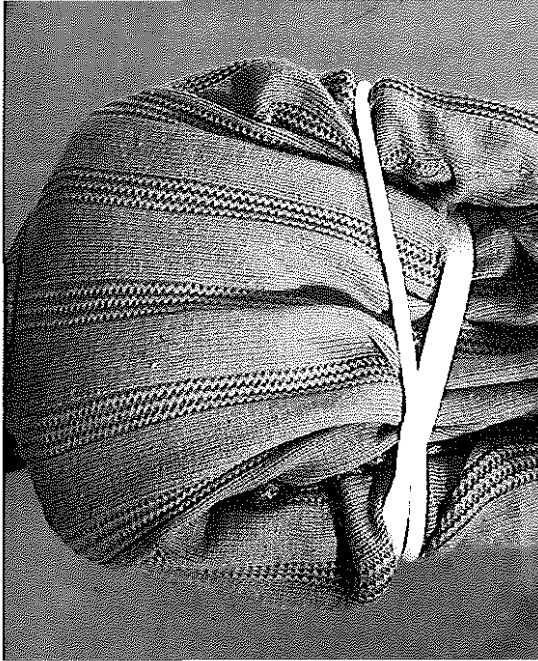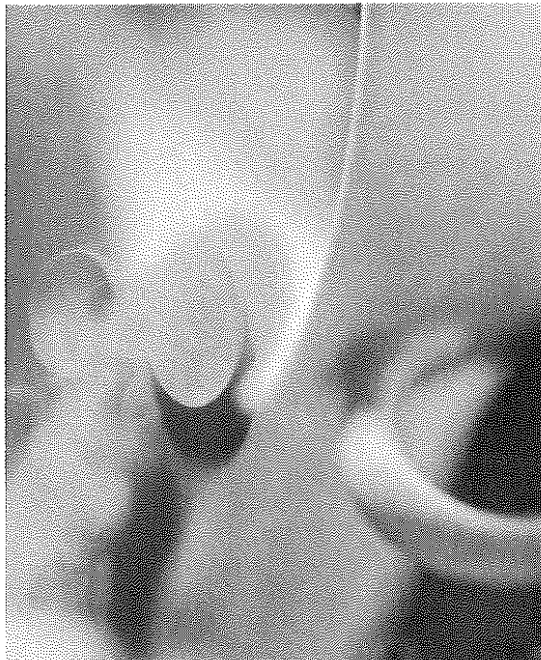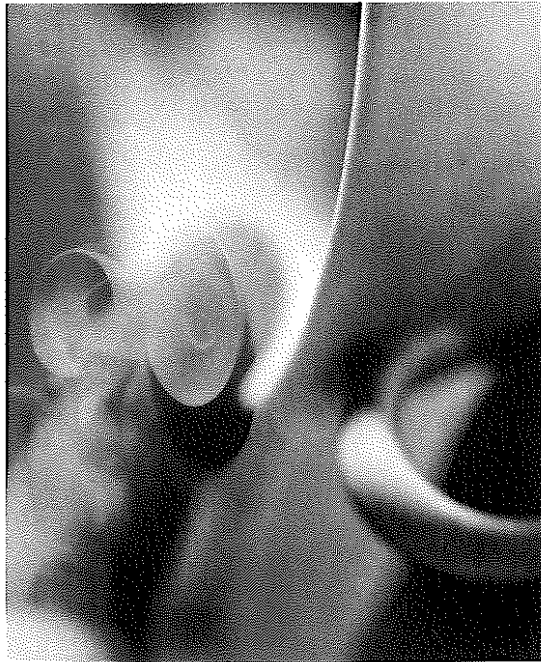
Fig. 1a.– Bound to Fail

Fig. 1b. – Coffee Spilled Because the Cup Was Too Hot
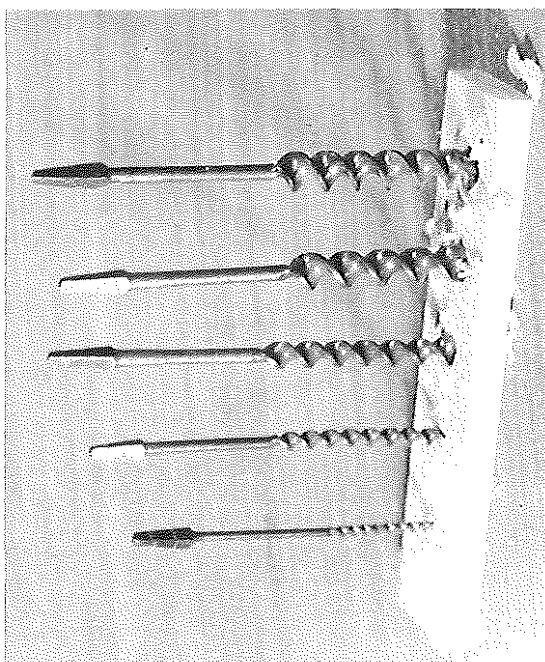
Fig. 1c. – Coffee Thrown Away Because the Cup Was Too Cold

Fig. 1d.– Drill Team

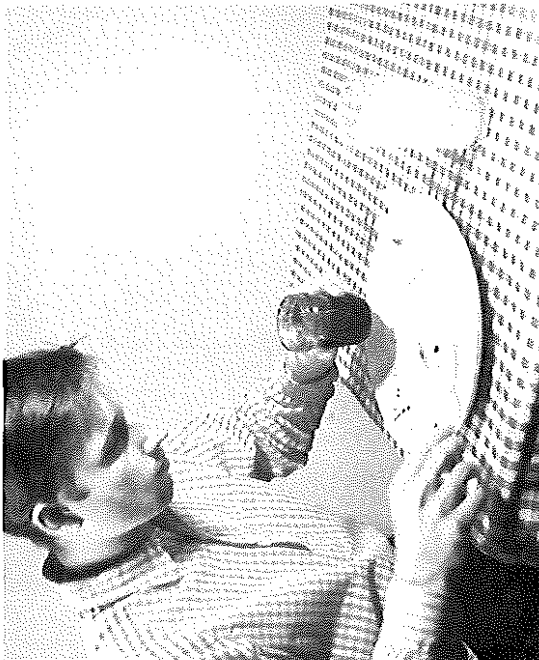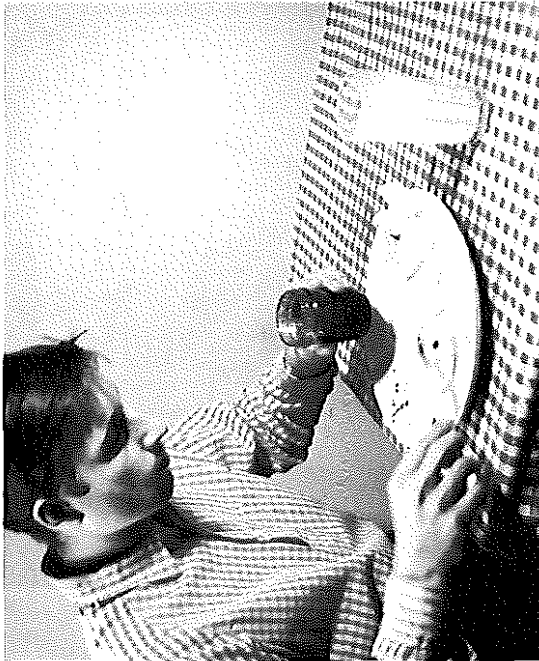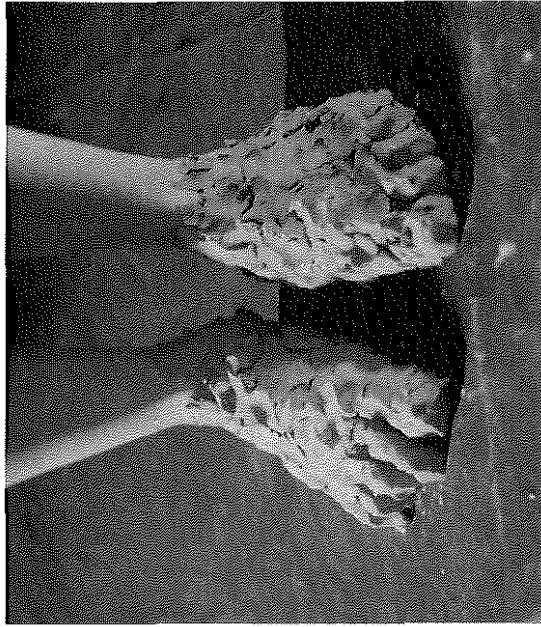Rudolf Gschwind and Franziska Frey
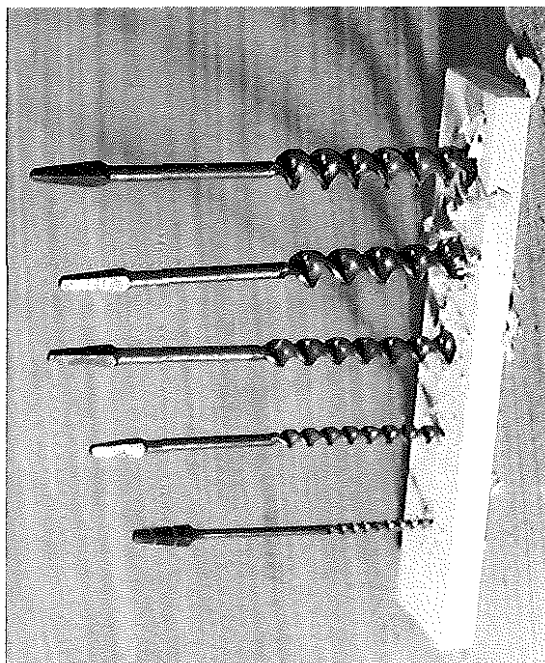
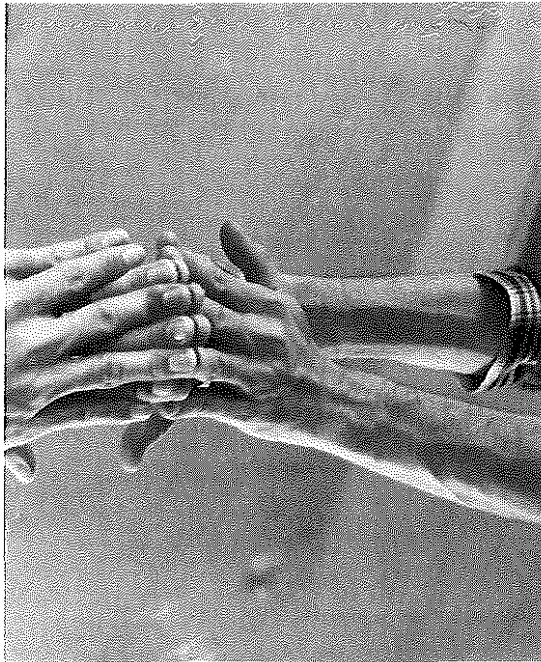Fig. 1e.– Eating My Words
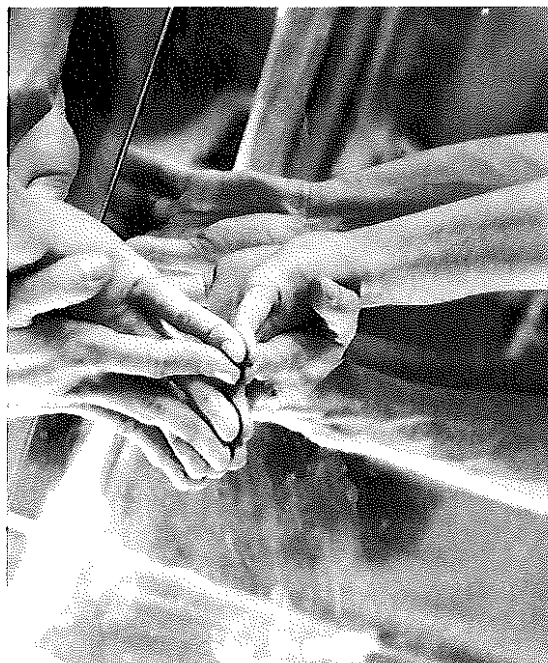
Fig. 1f – Feet of Clay
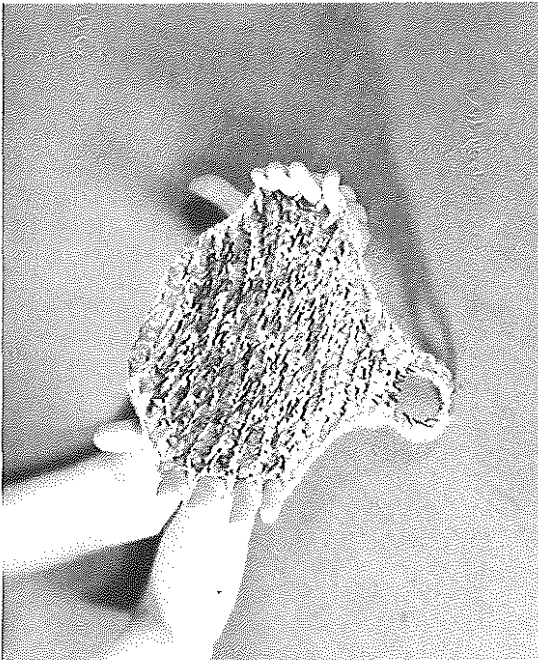
Fig. 1g. – Finger Touch N° 1
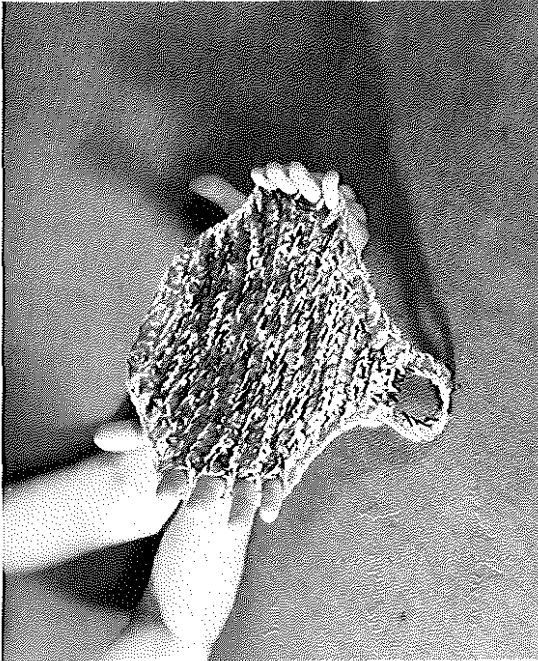
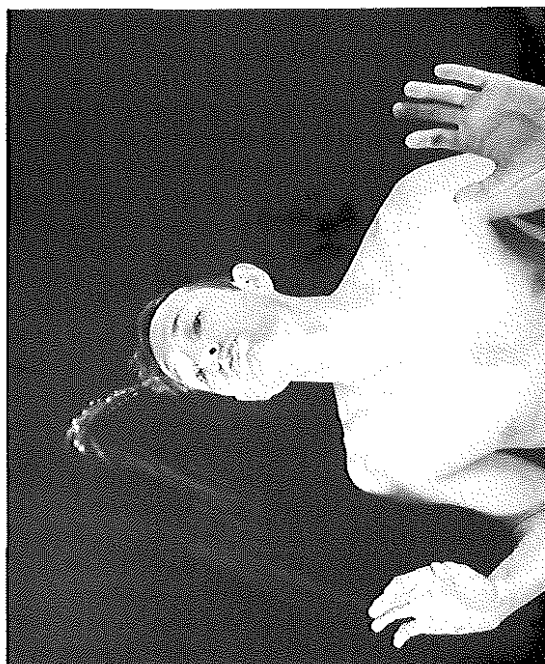Fig. 1h. – Finger Touch with Mirrors

Fig. 1i. – Self-Portrait as a Fountain
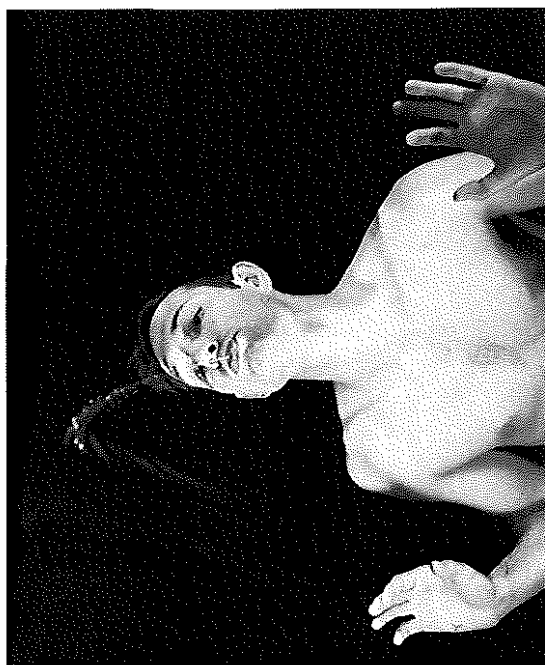
Fig. 1k.– Untitled (Potholder)
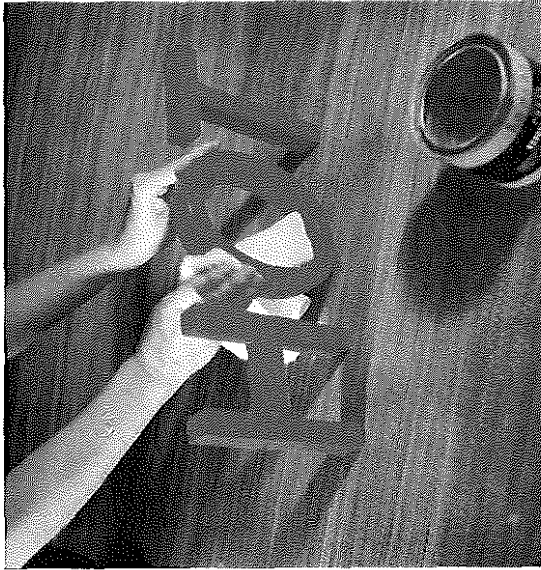
Rudolf Gschwind and Franziska Frey

Fig. 11.– Waxing Hot

2. Concept of the Digital Reconstruction Process

To carry out a color reconstruction the photographic bleaching processes have to be well known. From a chemical point of view, bleaching is a function of changes of the individual dyes. If it is possible to quantify the spectral (resp. concentration) changes of the dyes, the reconstruction is simple, at least in the laboratory. The procedure is as follows:

— produce color photographs with color test patches (gray- and color-wedges);

— determine the relationship $OD_{(bleached)} = f[OD_{(unbleached)}]$ by measuring the optical density OD of these patches before and after fading;

— digitize the faded photograph;

— apply the inverse of the relationship to calculate back the original densities of the colorants; and

— print the restored digital image, e.g., with a film recorder, on color film.

However in reality many problems occur. In most cases, the only available piece of information is the deteriorated photograph itself and nothing is known about the film type and the bleaching and storage conditions. Most of the time the photographs do not contain any known reference colors (the famous gray wedge). It is important to be aware that it is impossible to develop a reconstruction tool whereby one can simply choose film type and age, e.g., "Ektachrome, 1953," and obtain the reconstructed image automatically. Hence, a reconstruction implies the following procedure:

— Reconstruction must be carried out interactively under visual control and judgment of a human operator.

— In order for the colors of the image to be restored and not only retouched by subjective judgment, the reconstruction process must obey the laws of bleaching that are known from accelerated bleaching tests. Therefore, a mathematical bleach model is needed; this model should be as simple as possible while covering as many bleaching behaviors as possible.

3. Linear Bleach Model

The simplest model is one where each dye fades proportionally to its original concentration. However, bleaching is more complicated and may

involve other effects as, e.g., staining apart from the reduction of color density.

A valuable model for fading can be described by the following linear bleach equation:

$$\begin{pmatrix} Y' \\ M' \\ C' \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \times \begin{pmatrix} Y \\ M \\ C \end{pmatrix} + \begin{pmatrix} a_{14} \\ a_{24} \\ a_{34} \end{pmatrix}$$

where (Y, M, C) is the original optical density of the dyes (Yellow, Magenta, Cyan) and (Y', M', C') is the optical density of the faded dyes.

The equation describes different effects. Normally, the dyes fade proportionally to their original density (proportional to concentration). Bleaching may cause transformation of bleached or other even colorless substances into colored species as well. This is called staining. The additional coefficients a_{14}, a_{24}, a_{34} result from an increase or decrease of base density. Non zero base density occurs if staining of white elements has to be corrected or if the bleaching is not proportional but subtractive as often is the case in light fading. The amount of bleaching by light depends also on the density of the neighboring layers as they act as filters. This model is a more detailed description for the fading process as the Arrhenius stability data published by the manufacturers. Furthermore the 12 coefficients of the bleach equation will be called bleach matrix.

4. Accelerated fading test

Accelerated fading tests were carried out to get the required knowledge about the fading process. Various grey and color wedges were exposed on different photographic three color materials in order to cover the most significant parts of the RGB-cube. Then they were bleached under different conditions of illuminance, temperature and relative humidity. The temperatures for the dark fading tests were set to 60 °C, 70 °C and 80 °C. So the assumptions for the Arrhenius equation are also met and the results can be compared with results from literature [10]. To control the relative humidity, the test strips were put into dessicators above different saturated salt solutions (sodium chloride to get 75 %, sodium nitrate to get 65 % and sodium bromide to get 50 % rel. humidity [28].

For the photochemical tests light boxes with fluorescence lamps producing approximately 25,000 lux were used. Predictions from light

fading tests are difficult, because the photochemical fading depends not only on the intensity, but also on the duration and spectral energy distribution of the light causing the fading.

These test conditions accomplish the ISO Standard 10977 requirements [29]. But there is a difference between the image stability data described in the Standard and the data needed for the digital restoration. In the latter case the question of durability that means how long it takes, e.g., until 20 % of the cyan dye of a color material is bleached, is just secondary. First of all it is important to know the mechanism of bleaching exactly. Because only few is published about this field in literature, the accelerated fading tests had to be carried out.

Naturally today's film materials have to be used for the tests and the results are in fact only true for these materials. Former materials however can not be tested anymore and you even can not find any information about these materials. So what is done is an extrapolation of the results from today's materials to the former materials.

5. Experimental Results

Several modern color slide films were investigated, including Orwochrome UT 18 films which use the former type of color couplers employed also for the old Agfa films. The densities of the original and bleached films were measured using a standard color densitometer (Status A mode). The results for three films (Ektachrome 100, Kodachrome 64, and Agfachrome 100) shall be shown.

Figure 2 shows the results of the Ektachrome 100 dark fading test. As can be clearly seen, dark bleaching is proportional to the concentration of the original dye *i.e.* the original analytical density.

Figure 3 shows the stability of the same film towards high relative humidities. The oil-dispersed couplers of the Ektachrome 100 show a good stability behavior under the different bleaching conditions. But it should be mentioned that the relative humidity should not be to high for accelerated dark fading tests (recommended are 50 % relative humidity) [16,30].

Figure 4 shows the results of the Kodachrome 64 light fading test. In the case of light fading, bleaching becomes often subtractive as can be seen with the magenta dye of Kodachrome 64. In this case, the image

Table 1

Bleach matrix for Ektachrome 100 dark bleaching (see fig. 2)

Ektachrome 100 1000 h, 70°C/50%	0.95	0.01	0.01	0.12	$R = 0.998$
	0.01	0.81	0.05	0.04	$R = 1$
	0.01	−0.01	0.85	0.02	$R = 1$
Ektachrome 100 1800 h, 70°C/50%	0.75	0.05	0.00	0.22	$R = 0.993$
	0.05	0.70	0.08	0.07	$R = 1$
	0.02	0.0	0.73	0.03	$R = 1$
Ektachrome 100 2600 h, 70°C/50%	0.54	0.08	0.01	0.33	$R = 0.993$
	0.06	0.62	0.10	0.09	$R = 1$
	0.03	0.01	0.61	0.04	$R = 0.999$
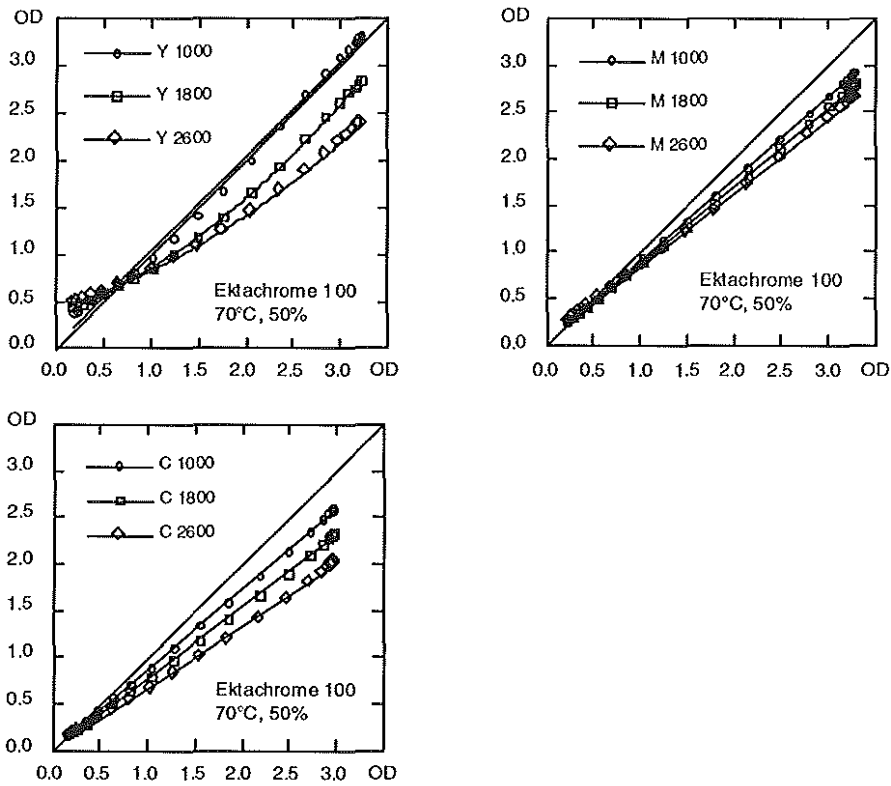
Fig. 2.– Ektachrome 100 dark fading (1000 hours/1800 hours/2600 hours, 70 °C, 50 % rel. humidity). Comparison of the integral densities (grey wedge) before and after fading (Y = Yellow, M = Magenta, C = Cyan). Fading is proportional to dye concentration. The yellow stain can be clearly seen.

Table 2

Bleach matrix for Ektachrome 100 dark bleaching under different relative humidities
(see fig. 3)

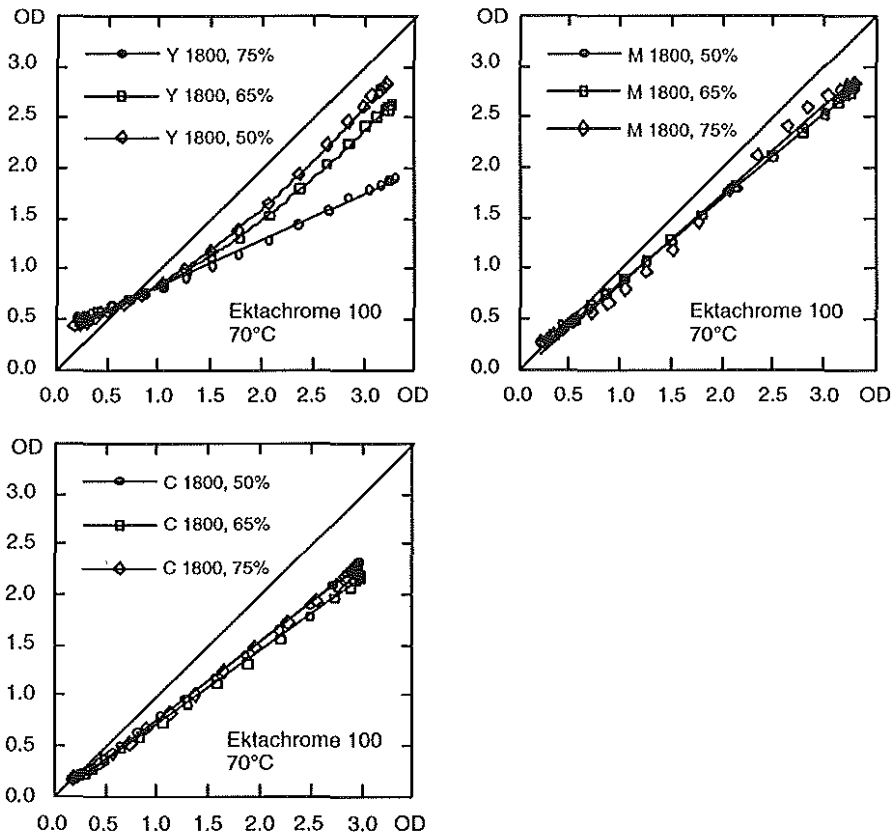| Ektachrome 100	0.75	0.05	0.00	0.22	$R = 0.994$
1800 h, 70 °C / 50 %	0.05	0.70	0.08	0.07	$R = 1$
	0.02	0.00	0.73	0.03	$R = 0.999$
Ektachrome 100	0.37	0.06	0.02	0.43	$R = 0.997$
1800 h, 70 °C / 75 %	0.29	0.46	0.15	−0.02	$R = 0.994$
	0.18	−0.01	0.57	0.04	$R = 0.999$

Fig. 3.– Ektachrome 100 dark fading (1800 hours, 70 °C, 50 % / 65 % / 75 % rel. humidity). Comparison of the integral densities (grey wedge) before and after fading.

Table 3

Bleach matrix for Kodachrome 64 light fading, emulsion layer towards light source. All data points are used for the calculation of the multiple linear regression. Due to the heavy subtractive bleaching of the magenta dye the correlation coefficient decreases to 0.95. See fig. 4.

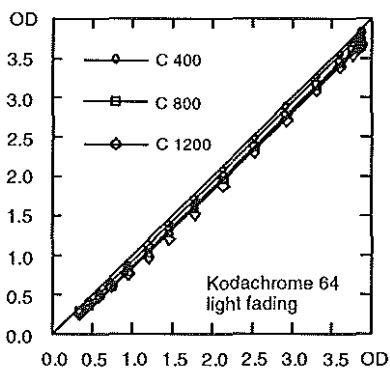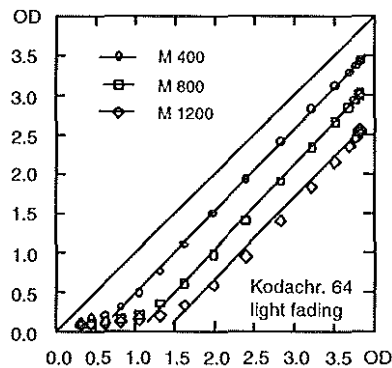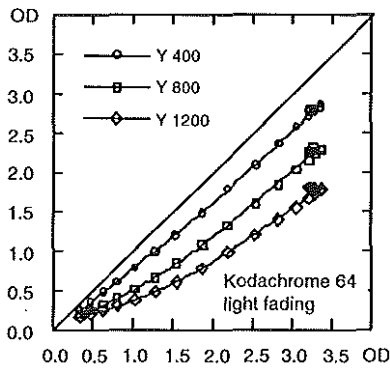| Kodachrome 64 400 h, light fading	0.82	0.01	0.03	−0.47	$R = 0.999$
	0.19	0.72	0.12	−0.46	$R = 0.991$
	0.28	−0.02	1.00	−0.08	$R = 1$
Kodachrome 64 800 h, light fading	0.63	0.00	0.05	−0.09	$R = 0.998$
	0.27	0.50	0.17	−0.60	$R = 0.972$
	0.05	−0.06	1.00	−0.14	$R = 0.999$
Kodachrome 64 1200 h, light fading	0.43	0.02	0.07	−0.07	$R = 0.996$
	0.26	0.34	0.17	−0.54	$R = 0.956$
	0.06	−0.09	1.00	−0.16	$R = 0.999$

Fig. 4.– Kodachrome 64 light fading (25,000 lux, 400 hours / 800 hours / 1200 hours), emulsion layer towards light source. Comparison of the integral densities (grey wedge) before and after fading. Fading can be heavily subtractive (magenta dye).

Table 4

Bleach matrix for Kodachrome 64 light fading, emulsion layer towards light source. All data points with an optical density > 0.3 are used for the calculation of the multiple linear regression. This yields a much better correlation coefficient for the magenta dye. See fig. 4.

Kodachrome 64	0.65	0.01	0.06	−0.19	$R = 0.991$
800 h, light fading	0.47	0.75	0.03	−1.62	$R = 0.992$
	0.10	−0.03	0.98	−0.32	$R = 1$
Kodachrome 64	0.45	0.04	0.07	−0.26	$R = 0.983$
1200 h, light fading	0.55	0.06	0.07	−1.91	$R = 0.986$
	0.14	0.05	0.98	−0.43	$R = 1$

information is totally lost and if the dyes are completely destroyed, a restoration is of course no more possible.

Figure 5 shows the results of the Agfachrome 100 light fading test. Light fading tests were always carried out twice. Once the base (fig. 5a), in the other case the emulsion layer (fig. 5b) was turned towards the light source. So the filtering effects of the neighboring layers can be studied. The yellow dye in figure 5b is faded much more because the yellow-layer is not protected against fading from another layer or from the base. The cyan dye on the contrary shows the opposite behavior.

The coefficients of the bleach equation were determined by multiple linear regression (tables 1 through 5). A goodness of fit measure is multiple correlation coefficient R which is always greater than 0.99, except for the Kodachrome magenta dye and the Agfachrome yellow dye in the case of light fading. This means that the model is well justified.

Table 5

Bleach matrix for Agfachrome 100 light fading. Once the base was turned towards the light source, in the other case the emulsion layer. See fig. 5.

Agfachrome 100	0.57	0.17	0.18	−0.27	$R = 0.998$
1000 h, light fading,	0.02	0.61	0.26	−0.18	$R = 0.994$
base towards light	0.01	−0.03	0.84	0.01	$R = 0.999$
Agfachrome 100	0.30	0.07	0.06	0.05	$R = 0.978$
1000 h, light fading,	0.07	0.60	0.11	−0.13	$R = 0.994$
emulsion layer towards light	0.03	−0.03	0.97	0.06	$R = 1$
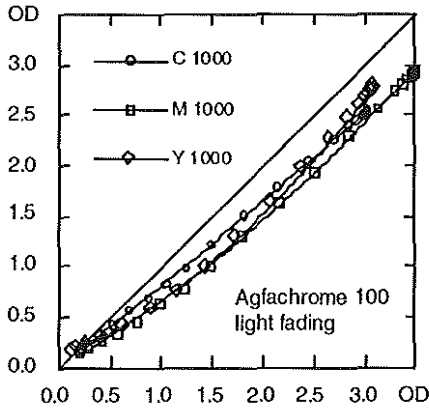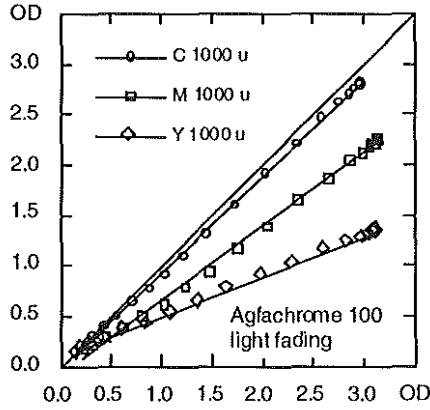
a   **b**

Fig. 5.– Agfachrome 100 light fading (25,000 lux, 1000 hours). Comparison of the integral densities (grey wedge) before and after fading: a) base turned towards the light source; b) emulsion layer turned towards the light source. Filtering effects can be clearly seen.

Fig. 6a.– Ektachrome 100 dark fading, yellow dye (100 h–500 h, 80 °C, 75 % rel. humidity). Comparison of the integral densities (grey wedge) before and after fading. The optical density in the blue increases during the beginning of the incubation time.

Fig. 6b.– Kodachrome 64 dark fading, magenta dye (100 h–500 h, 80 °C, 75 % rel. humidity). Comparison of the integral densities (grey wedge) before and after f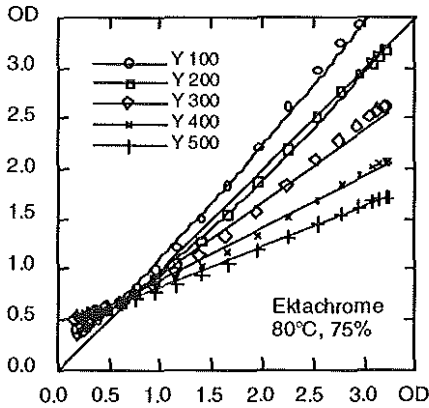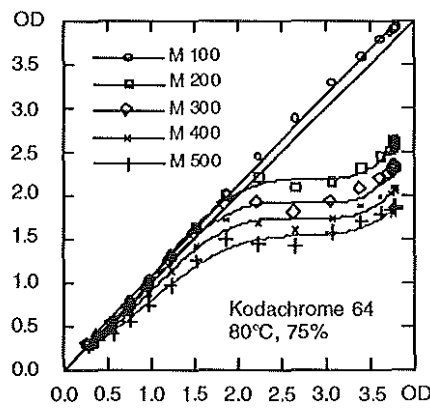ading. In the case of high temperatures and high relative humidities, the magenta dye shows a strong non-linear behavior.

Table 6

Results of the dark fading tests of the tested slide films. The
rating of the stability was carried out with a scale ranging from
1 to 5 (1 for the most stable, 5 for the least stable material).

Filmtype	Relative stability	Stain	Stability towards rel. humidity (ratio 50 % / 75 %)	Linear bleach model	Remarks
Ektachrome 100	2	yes	good, except yellow dye	yes	in the case of high relative humidities the optical density in the blue increases during the beginning of the incubation time
Agfachrome 100	2	yes	good, except yellow dye	yes	in the case of high tempe- ratures droplets appear at the surface of the film. After a longer incubation time, crystallization spread out around these spots
Orwochrome UT18	4	no	bad, all dyes severely react	yes	non-linearities in the case of high relative humidities
Kodachrome 64	1	no	sufficient, yellow dye and magenta dye considerably react	yes	non-linearities in the case of high temperatures and high relative humidities
Ektachrome Duplicating	2	yes	good except yellow dye	yes	
Fujichrome Duplicating	2	yes	good	yes	in the case of high relative humidities the yellow dye shows diffusion

Bleaching is in most cases proportional to the concentration. Excep-
tions arise above all when the test were carried out with high temperatures
combined with high relative humidities. Figure 6a shows the results of
Ektachrome dark fading tests (for the yellow dye). Here, the optical
density in the blue increases during the beginning of the incubation time.
Figure 6b shows the results of Kodachrome dark fading tests (for the
magenta dye). The magenta dye shows under this test conditions a strong
non-linear behavior. But one has to be careful with the interpretation
of this results because often this effects just happen under this heavy
bleaching conditions. To sum up it should be noted that the accelerated
fading tests should be carried out under several different fading conditions

Table 7

Results of the light fading tests of the tested slide films. The
rating of the stability was carried out with a scale ranging from
1 to 5 (1 for the most stable, 5 for the least stable material).

Filmtype	Relative stability	Stain	"Substractive behavior"	Remarks
Ektachrome 100	2	no	yes, magenta dye	
Agfachrome 100	3	no	visible for magenta dye	pronounced filtering effects
Orwochrome UT18	3	no	visible for magenta dye	the cyan dye shows non-linearities
Kodachrome 64	4	no	pronounced for yellow and magenta dye	the magenta dye shows a pronounced subtractive behavior
Ektachrome Duplicating	2	no	visible for magenta dye	
Fujichrome Duplicating	1	no	visible for yellow and magenta dye	

to make sure that the observed behavior is equal to the real behavior
under normal bleaching conditions [30].

Tables 6 and 7 show a summary of the test results for the accelerated
dark fading and light fading tests (including all tested slide film materials).

6. Print Materials

Tests were carried out with chromogenic negative-positive (Kodak
Ektacolor, Agfacolor) as well as a direct positive silver-dye-bleach (Ilfo-
chrome) print material. In the case of print materials the bleaching con-
ditions are often complicated, and fading is mostly a combination of light
and dark fading. Additionally the prints are often glued in albums and
you will get all the problems of glue and acid card board. The reflection
densities of the different wedges were measured with a spectrophotometer
from 380 to 730 nm in steps of 10 nm. This method of measurement yields
the possibility to see whether new dyes with a different spectral behavior
were formed.

Figure 7 shows the case of the magenta dye of Agfacolor paper
after dark and light fading. In case of dark fading, the dye bleaches and
simultaneously a yellowish stain is formed (fig. 7a). In case of light fading
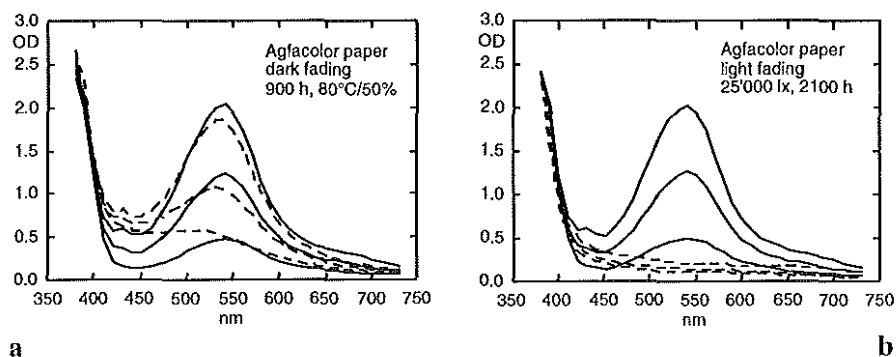
Fig. 7.– Reflection spectra of the magenta dye of Agfacolor Paper (three steps of the magenta wedge, unbleached and bleached state): a) dark fading; b) light fading.

the magenta dye is bleached subtractively *i.e.* the image information in bright parts is totally lost (fig. 7b).

Figure 8 shows the behavior of the cyan dye in Ilfochrome paper. The azo dyes used in silver-dye-bleach materials are markedly less fugitive to light and also much more stable against dark fading [31,32]. Due to aggregation the cyan dye shows a shift in its absorption maximum depending on the dye concentration. Under the influence of humidity in dark fading, a strong disaggregation takes place causing a strong shift and change of shape of the spectra (fig. 8a). In case of light fading however the dye bleaches but the spectrum keeps its normal shape. No disaggregation takes place because strong light has a drying effect on the layer (fig. 8b).
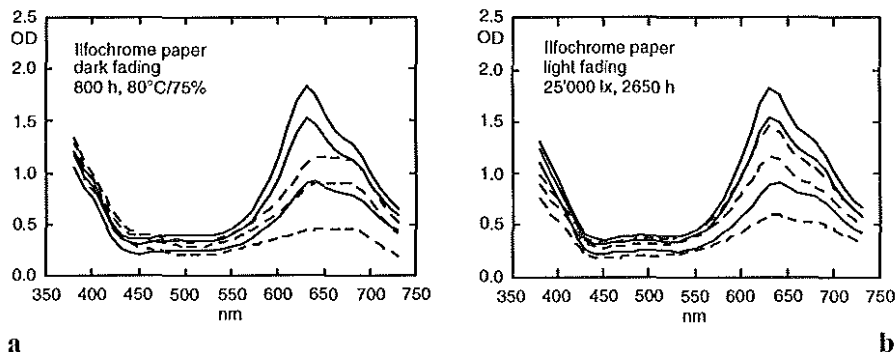

Fig. 8.– Reflection spectra of the cyan dye of Ilfochrome Print Material CPS1.K (three steps of the cyan wedge, unbleached and bleached state): a) dark fading; b) light fading.

Measured reflection densities have to be converted into transmission densities, because only transmission densities obey the Beer-Lambert

law which states, that the optical densities are proportional to the concentration of the dyes. This is done using the Williams Clapper function [33]. To determine how many dyes are forming the image a principle component analysis (PCA) was carried out.

For Agfacolor paper (fig. 9a) the PCA yields only 3 distinct eigenvalues for the unbleached as well as the bleached state (the higher eigenvalues are near zero). This means, that the image is formed of only three dyes and scanning of the bleached image with three filters is enough.

Fig. 9a.– The first five normalized eigenvalues of the principal component analysis of the dye spectra of Agfacolor print material before and after dark fading (800 h, 80 °C, ≈ 75 % rel. humidity): a) unbleached state, b) bleached state, c) both states together.

If the data of both states together were taken into account a forth distinct eigenvalue shows up representing the stain. But this stain can be easily subtracted because it is formed in a constant amount throughout the whole image. The stain must be formed out of residual, unused couplers which renains in large quantities in the photographic emulsion.

Ilfochrome print material (fig. 9b) shows an even more complex behavior. Note that the shift in the absorption maxima of the cyan dye leads to a forth distinct eigenvalue for the original image. Taking into account both states, even a fifth eigenvalue appears.

Tables 8 and 9 show a qualitative summary of the test results for the accelerated dark fading and light fading tests.
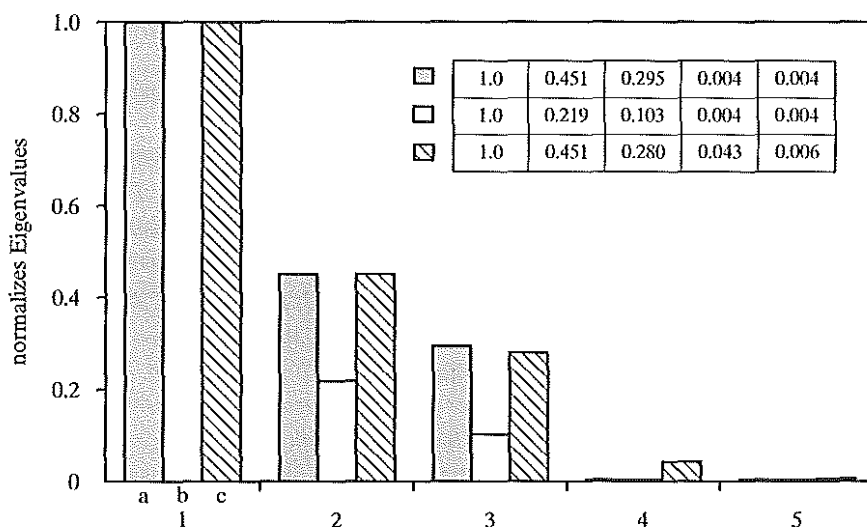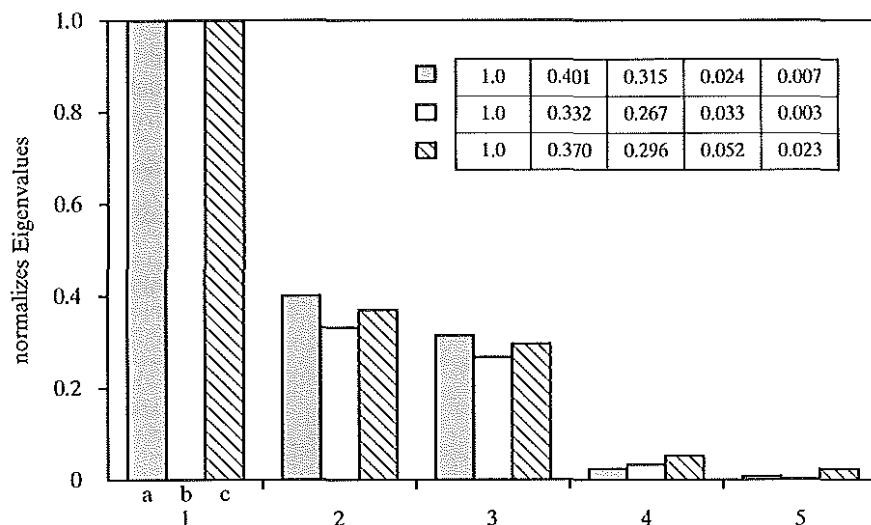
Fig. 9b.– The first five normalized eigenvalues of the principal component analysis of the dye spectra of Ilfochrome print material before and after dark fading (800 h, 80 °C, ≈ 75 % rel. humidity): a) unbleached state, b) bleached state, c) both states together.

7. Discussion and Conclusion about the Fading Process

The tests on the bleaching behavior show, that the linear bleach model is a good description of the bleaching process. Under moderate dark fading conditions bleaching is proportional to dye concentration. That corresponds to a first-order kinetic what would be expected from chemical considerations. In case of dark fading there is often a stain formed. This implicates some problems for the evaluation of dark stability using Arrhenius' law. The calculated stability value will be dependent on the selected original density value and furthermore on the duration of the accelerated tests.

In case of light bleaching you often see a different behavior. The bleach equation still fits but the destruction of the dyes is subtractive, *i.e.* the same amount of dye is destroyed everywhere. In chemical terms this is a zeroth-order kinetic.

In extreme cases (strong light, high humidity, ...) bleaching becomes non-linear and a more complicated model is needed for fitting the data. This could be done e.g., by a higher order polynomial expansion.

Table 8

Results of the dark fading tests of the tested print materials.
The rating of the stability was carried out with a scale ranging
from 1 to 5 (1 for the most stable, 5 for the least stable material).

Print material	Relative stability	Stain*	Stability towards rel. humidity (ratio 50 % / 75 %)	Linear bleach model	Remarks
Agfacolor	3 yellow dye shows the lowest stability	P	sufficient magenta dye considerably reacts	yes	the turning yellow of residual chemicals is mainly responsible for the heavy stain in the case of high temperatures and high relative humidities
Ektacolor Plus	3 yellow dye shows the lowest stability	P	good yellow dye considerably reacts	yes	the turning yellow of residual chemicals is mainly responsible for the heavy stain in the case of high temperatures and high relative humidities
Ilfochrome	1	W	cyan and magenta dye considerably react	highly concentrated azo-dyes show deviations from the Beer-Lambert law	in the case of high temperatures the protection layer shows "craquelure" effects.

* P = pronounced; W = weak.

The use of a more sophisticated reconstruction model, which would handle all bleaching behaviors, especially under heavy bleaching conditions, would have too many free variables and would therefore be too indeterminated. Moreover, additional effects, such as inhomogenous bleaching or complete destruction of the dyes, occur, and they are much more problematic for the reconstruction than an "incorrect" bleaching model.

Table 9

Results of the light fading tests of the tested print materials. The
rating of the stability was carried out with a scale ranging from
1 to 5 (1 for the most stable, 5 for the least stable material).

Print material	Stability	Stain	Substractive behavior	Linear bleach model	Remarks
Agfacolor	4	slight	magenta dye considerably reacts	yes	in the case of a heavily subtractive bleaching, a reconstruction is no longer possible
Ektacolor Plus	3	slight	magenta dye considerably reacts	yes	in the case of a heavily subtractive bleaching, a reconstruction is no longer possible
Ilfochrome	1	hardly	no	highly con-centrated azo-dyes show deviations from the Beer-Lambert law	

8. Practical Aspects of the Reconstruction Procedure

There is a further complication: scanners or densitometers measure
the so-called integral densities. The optical density OD of a color film
depends on the sum of the three single dye densities, yellow, magenta
and cyan (Y, M, C). The resulting OD is called integral density. The
absorptions of the individual dyes, which is called analytical density,
cannot be measured directly, but must be calculated from the integral
densities of all three dyes. This calculation implies that the absorption
spectra of the individual dyes are known.

In reconstructing images analytical densities are needed for two
reasons. First, bleaching is, as mentioned above, a function of the
concentrations of the individual dyes and therefore of the analytical
densities. The second reason concerns color reproduction, *i.e.*, the
problem of the side absorptions of the dyes. This point becomes even
more important for heavily bleached photographs. If the reconstruction is
based only on integral densities, the contrast of the reconstructed image is
correct, but the image shows poor color rendition with desaturated colors.

The following example shall demonstrate the effects of using integral
instead of analytical densities for reconstruction.

Figure 10 shows a film in which cyan has been bleached to 20 %,
i.e., by a factor of 5. An originally neutral gray has turned reddish.
This neutral gray will be used for the calibration. This means that the
cyan contrast is increased until the resulting color becomes gray again.
The integral density measured at 650 nm after bleaching is 0.3. A
multiplication factor of 3.5 is needed to get back the original density of 1.1.
Note that the integral density measured at 650 nm depends substantially
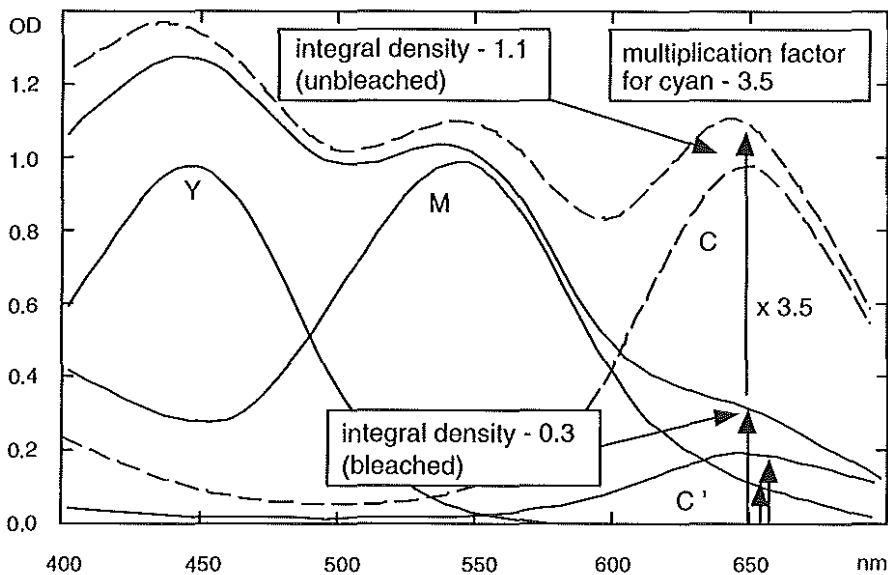on the side absorption of the magenta dye.

Fig. 10.– Hypothetical film, in which cyan has been bleached to 20 %, *i.e.*, by a
factor of 5. However the integral density in the red (at 650 nm) changes just
from OD = 1.1 to OD = 0.3. Thus the resulting multiplication factor for the
reconstruction of cyan equals only 3.5 ($\approx$ 1.1/0.3), because the side absorption
of magenta in red is quite important compared with that of the bleached cyan.

In the case of an originally pure red color (yellow + magenta dye,
fig. 11a) problems occur if you do not consider the side absorption of the
magenta dye, which simulates the presence of cyan. If we multiply the
"wrong" cyan (originating from the side absorption of the magenta dye)
by the factor 3.5 the restored red is too dark and unsaturated.

Fig. 11a.– Hypothetical film, in which cyan has been bleached. A reconstruction based on integral densities of a pure red color containing no cyan yields a dark and unsaturated red. The side absorption of the magenta in the red is about OD = 0.1, which results in a false reconstruction of cyan by a factor of 3.5.
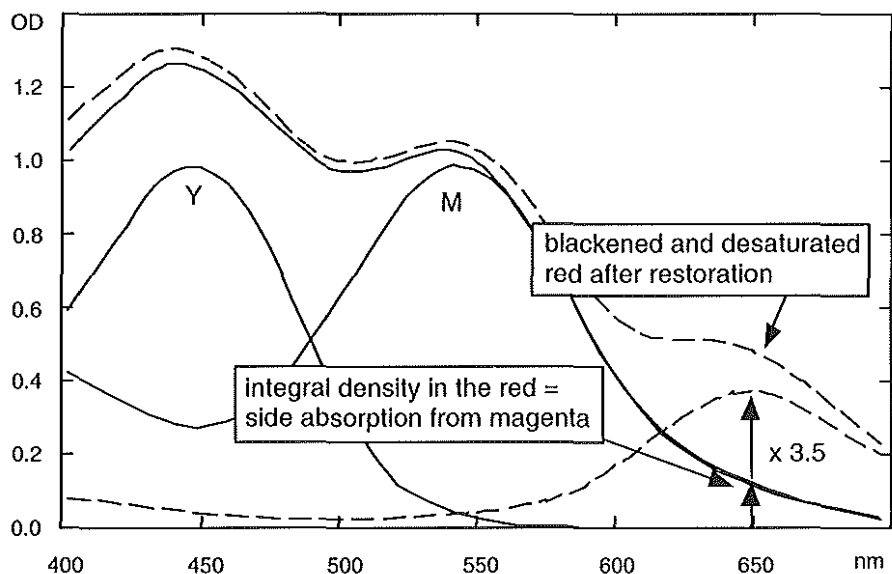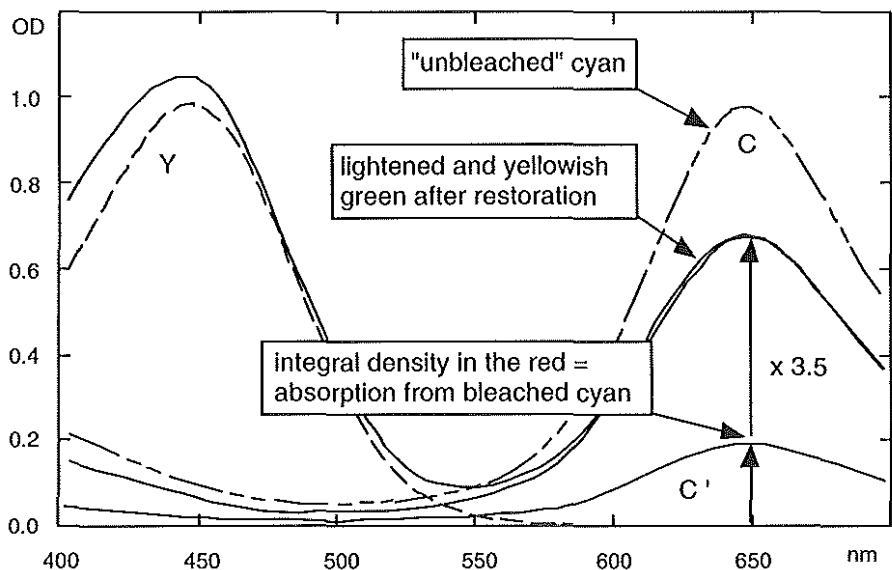

Fig. 11b.– Hypothetical film, in which cyan has been bleached. A reconstruction based on integral densities of a pure green color containing no magenta yields a lightened and yellowish green. In this case the multiplication factor of 3.5 is too small.

In the case of the reconstruction of a green (yellow + cyan, fig. 11b) color, there is no red absorption of the magenta dye, and the multiplication factor of 3.5 is too small to restore the bleached cyan. The restored green is too yellowish and light.

If the reconstruction is based on analytical densities, the color reproduction is correct. The problem of side absorptions is well known in the photographic field and is solved either by color masking techniques or by chemical methods, e.g., DIR couplers [34].

For the reconstruction, the operator treats the displayed digitized image on the computer, following the bleaching model until the correction is satisfactory. Because it is difficult to estimate the coefficients of the linear bleach equation directly, the user may work with the more familiar visual and photographic parameters: hue, contrast, brightness, and color cast. The program converts these parameters to coefficients of the bleaching equation. Once the correction is satisfactory, the final coefficients of the bleaching equation are used to transform the input image, and the reconstructed image is exposed on color film with a high-resolution film recorder.

9. Color Reproduction Aspects

An important step is scanning the photograph. Concerning the color reproduction, two aspects must be considered:
— The photometric resolution must be a minimum of 10 bits per channel or even more, as color photographs, especially slides, show a high dynamic brightness range.
— Channel separation must be done with narrow-band interference filters (e.g., 450, 550, and 650 nm, halfwidth $\approx$ 20 nm) to achieve good spectral resolution.

As mentioned above, the needed accurate information about the concentration of the dyes can be obtained by applying the Beer-Lambert law, which states that the OD is proportional to concentration. This law is true only for monochromatic light. Ordinary color scanners, however, are equipped with broad-band color separation filters, and the Beer-Lambert law does not hold. The aim of most commercial color scanners is to measure colors and not colorants, *i.e.*, pixel values should represent colorimetric data (CIELAB, XYZ, ...). This means that the spectral sensitivities of the three scanner sensors must be broad, because they have

to fit the colorimetric tristimulus curves. Figure 12 shows an example. The broken lines represent the spectral sensitivity curves of a commercial CCD camera of that type. With a suitable linear combination of the sensor signals, one can fit the CIE 1931 tristimulus-values from the three spectral sensitivities (S_{blue}, S_{green} and S_{red}) of the camera.
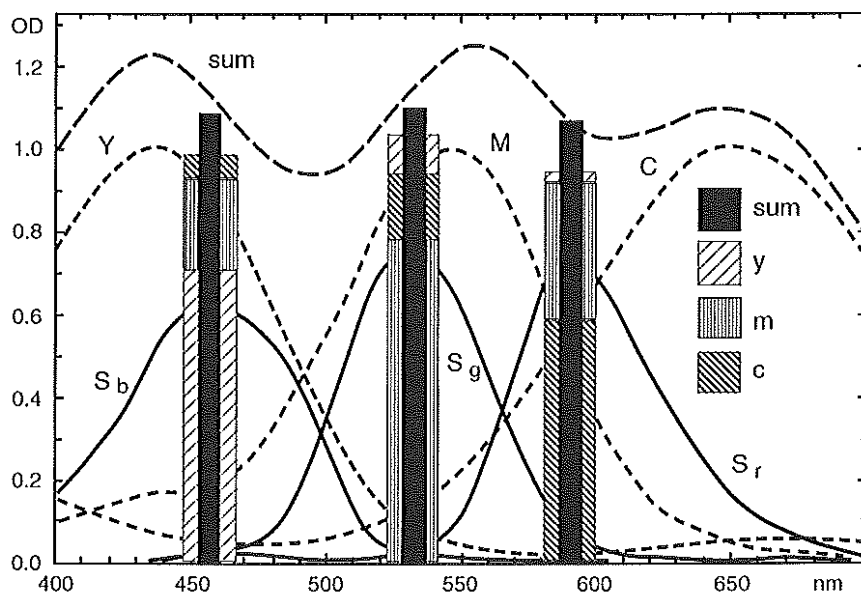

Fig. 12.– Spectral sensitivity curves S_b, S_g, S_r of a CCD camera (*broken lines*), and the absorption curves of today's photographic dyes (*full lines*). The *bars* represent the printing densities as seen by the CCD camera for the individual dyes (*hatched bars*) and the integral sum (*black bars*).

As figure 12 shows, the spectral halfwidths are very large compared with the absorption bands of today's photographic dyes, and the red sensitivity, with a maximum at 590 nm, is much too short relative to the absorption maxima of the cyan dye ($\approx$ 650 nm). The determination of analytical densities with such broadband sensitivities is problematic, as shown in figure 12. The gray bars represent the OD for the sum of all three dyes (= gray), as they would be measured with this scanner, *i.e.* they represent the so-called printing densities [35]. The colored bars (yellow, magenta or cyan) represent the printing densities of each dye in its pure state.

Two points have to be emphasized:

1) The sum of the printing densities of the dyes in their pure states (total length of the colored bars) is less than the printing density (length of the gray bars) of the three dyes together. This is a direct result of the broad spectral sensitivities of the scanner. As a consequence analytical densities can only be estimated roughly. With narrow-band sensitivities (e.g., narrow-band interference filters in front of the light source) we do not have this inaccuracy, because in this case the Beer-Lambert law is fulfilled.

2) The sensitivity of the red "colorimetric" sensor is just in between the absorption maxima of the magenta and cyan dyes and therefore the measured OD in the red does not originate mainly from the cyan absorption, but nearly half of it comes from the side absorption of the magenta dye, as is seen in figure 12. This situation is especially critical for color films in which the cyan dye has bleached predominantly. In this case, the "red sensor" of a colorimetric camera detects more or less only the magenta side absorption, and a correct reconstruction is no longer possible. These types of colorimetric scanners are also problematic for color negative materials, as the absorption maximum of the cyan dye in commercial color negatives is at an even longer wavelength, ca. 700 nm.

10. Determination of Dye Spectra of Bleached Photographic Materials

For a correct reconstruction (*i.e.*, for the determination of analytical densities), the dye spectra of the bleached films should be known. For today's materials this is no problem, as the manufacturer supplies this information. But for older bleached materials it is difficult or even impossible to obtain the spectra. The manufacturer (if he does still exist) no longer has information, and additionally we often know neither film type nor manufacturer.

This lack of knowledge about the dye spectra of the bleached films presents problems in the described reconstruction method. Therefore an estimation of the spectra by means of a spectroscopic analysis of the bleached materials is needed.

Especially in the case of heavily bleached films it is important to know the absorption maxima of the dyes to be able to measure the OD at these wavelengths. Figure 13 shows the spectra of several bleached films
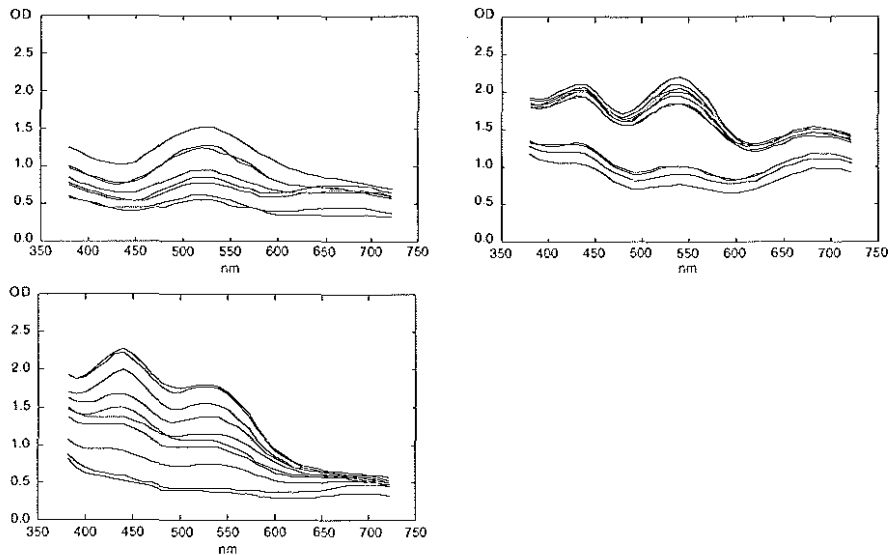
Fig. 13.– Different spectra of old bleached slide films. (a) Kodachrome, 1937; (b) Agfa-color, 1943; (c) unknown film type, 1956. It can be clearly seen that the cyan dye absorption maxima are at much longer wavelength than is characteristic of today's materials.

measured by a spectrophotometer. The absorption maxima of the dye spectra indicate which narrow-band interference filters have to be used for scanning. Above all, the cyan dyes of the older materials often have absorption maxima at longer wavelengths than today's materials.

Furthermore the possible spectra of the dyes used have to be estimated. A method for the determination of the spectral density distributions of the component dyes from those of their mixture is described by Ohta et al. [36, 37]. It consists of measuring spectra from different color patches on the photographic color material and applying a principal component analysis. This results in eigenvalues, which indicate how many colorants (normally 3) the patches comprise and the corresponding eigenspectra. The eigenspectra are not the real dye spectra, but by applying a linear transformation of the eigenspectra obtain a set of possible spectra, among which are the real dye spectra. To obtain these spectra, two constraints are assumed: (a) spectral density distributions are always non negative, and (b) dye amounts to build up mixtures are always non negative. For a detailed description see [36].

As long as the color patches for the analysis contain the pure or mostly pure dyes, this method yields a good estimation of the 3 dye spectra. But in the case of bleached color photographs, we do not have
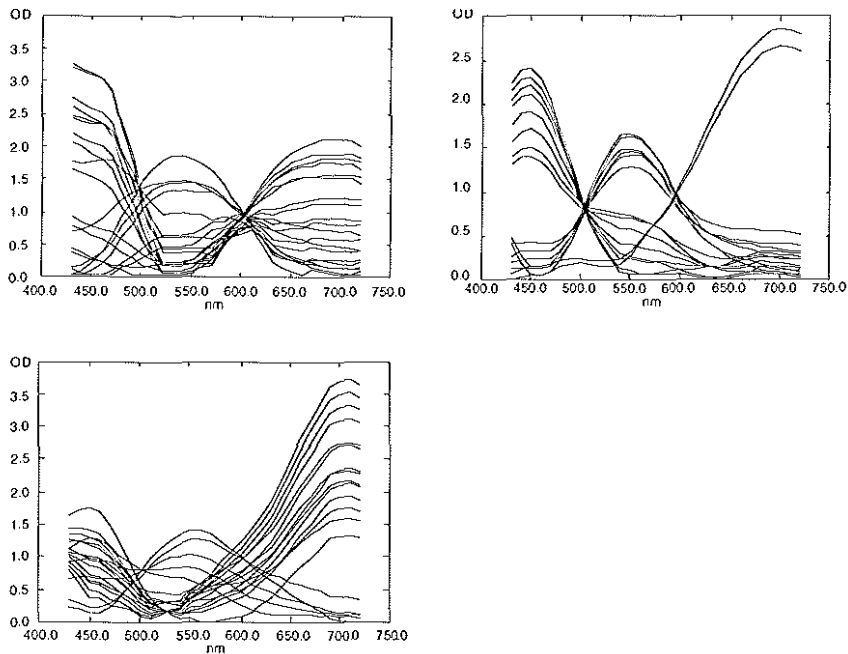
Fig. 14.– Set of possible spectra: (a) Kodachrome, 1937; (b) Agfacolor, 1943;
(c) unknown film type, 1956, determined by the method described in [13].

"color charts," but only scenes with a mostly restricted color gamut, *i.e.*,
mixed colors, so we determine a set of possible spectra. The more the
films are bleached, the larger the set of possible spectra. The spectra must
then be interpreted by means of photographic knowledge. Figures 14a–c
shows the results of the methods described applied to the dye spectra of
figures 13a–c.

Another possibility for the determination of the dye spectra would
consist of scratching away the different layers and examining each dye
individually. The disadvantage of this method is that the bleached
originals become partially destroyed.

11. Conclusion

Digital color reconstruction yields excellent results as long as bleaching is homogeneous throughout the whole photograph. Complications arise if the degradation is accompanied by the formation of colored spots. This happens frequently when slides are mounted between glass plates. Reconstruction of such defects is impossible by global procedures. Methods of electronic retouching have to be applied.

If the dyes of a photograph are completely destroyed, as often occurs in the case of light fading, reconstruction is no longer possible.

Because there is still a subjective part to the reconstruction process, the problems of color reproduction must be solved. One must know what has to be reconstructed: the original photograph, the original colors, the most pleasing image, or even if the reconstruction should correct defects (e.g., an overexposure) of the original photograph.

If there is only a single slide of a certain film type available for reconstruction, some problems can arise. In such a case there are too many degrees of freedom for the color reproduction. If a slide contains a gray wedge, the different brightness levels of the photograph can certainly be calibrated, but it does not help in calibrating the colors. When a whole series of photographs of a certain material type has to be restored, one can take the average of the different reconstruction parameters. This will yield better results.

There still remain a few questions that must be analysed carefully above all in the field of color reproduction. However the results reached so far are very promising, and the digital reconstruction is a powerful method to preserve color photographs as a cultural value of our century.

Bibliography

[1] GSCHWIND (Rudolf): 1990, "Restoration of Faded Colour Photographs by Digital Image Processing", *The Journal of Photographic Science*, 38, p. 193.

[2] GSCHWIND (Rudolf) and FREY (Franziska): 1991, "Digitale Bildverarbeitung: Restaurierung ausgebleichter Farbfotografien", Schweizer Ausgabe 1991 der *Jahresausgabe zur Chemischen Rundschau*, p. 17–21.

[3] GSCHWIND (Rudolf): 1991, "La dégradation des photographies couleurs et leur restauration à l'aide d'un ordinateur", in *Sauvegarde et conservation des photographies, dessins, imprimés et manuscrits*, Actes des journées internationales

d'études de l'ARSAG, Paris, Oct. 1991 (Association pour la Recherche Scientifique sur les Arts Graphiques, 36, rue Geoffroy-Saint-Hilaire, 75005 Paris, France).

[4] GSCHWIND (Rudolf) and FREY (Franziska): 1992, "Reconstruction of faded colour photographs by digital image processing", *Conference Proceedings of EVA'92* (Electronic imaging and visual arts), London, 29.–31. Juli 1992, (A. Hamber ed.), ISBN 0-9519980-3-X; published by Brameur Ltd, 237 High Street, Aldershot, Hants GU11 1TJ, England.

[5] WALLACE (J.): 1991, "The Use of Commercial Scanners to Restore Dark-Faded Color Transparencies", *J. Imaging Technology*, 17 (3), p. 107

[6] BRAUDQWAY (C.): 1993, "Restoration of Faded Color Transparencies by Digital Image Processing", *Paper Summaries IS&T's 46th Annual Conference* (Cambridge, May 1993, IS&T', The Society for Imaging Science and Technology, 7003 Kilworth Lane, Springfield, Virginia 22151 USA, 283-286, ISBN 0-89208-171-6).

[7] GSCHWIND (Rudolf) and FREY (Franziska): 1993, "Restoration of Faded Color Photographs by Digital Image Processing", *IS&T's 46th Annual Conference* (Boston, May 1993, IS&T, The Society for Imaging Science and Technology, 7003 Kilworth Lane, Springfield, Virginia 22151 USA, ISBN 0-89208-171-6), p. 281–283.

[8] GSCHWIND (Rudolf) and FREY (Franziska): 1994 , "Restoration of Faded Color Photographs and Color Movies by Digital Image Processing", *ICPS'94: The Physics and Chemistry of Imaging Systems, IS&T's 47th Annual Conference* (Rochester, 15–20 May 1994, The Society for Imaging Science and Technology, 7003 Kilworth Lane, Springfield, Virginia 22151 USA, ISBN 0-89208-177-5), p. 522–523.

[9] GSCHWIND (Rudolf), ROSENTHALER (Lukas), GRAFF (Werner) and FREY (Franziska): 1994, "Reconstruction of Faded Color Photographs and Color Movies by Electronic Imaging", in *Environnement et conservation de l'écrit, de l'image et du son*, Actes des deuxièmes journées internationales d'études de l'ARSAG, Paris, 16 au 20 mai 1994 (Association pour la Recherche Scientifique sur les Arts Graphiques, 36, rue Geoffroy-Saint-Hilaire; 75005 Paris, France), p. 252.

[10] GSCHWIND (Rudolf) and FREY (Franziska): 1994 , "Electronic Imaging, a Tool for the Reconstruction of Faded Color Photographs", *J. of Imaging Science and Technology*, 38 (6), p. 520.

[11] ANDO (Yujiro): 1995, *Digital Reconstruction of Faded Color Image*, conference on Managing and Preserving Image Collection held in Bangkok on Nov. 4, 1995.

[12] ANDO (Yujiro), HANSUEBSAI (Aran) and KHANTONG (Kanmanus): 1997, "Digital Restoration of Faded Color Images by Subjective Method", *J. of Imaging Science and Technology*, 41 (3), p. 259–265.

[13] FREY (Franziska) and GSCHWIND (Rudolf): 1993, "Mathematical bleaching models for photographic three-color materials", *IS&T's 46th Annual Conference* (Boston, May 1993, IS&T', The Society for Imaging Science and Technology, 7003 Kilworth Lane, Springfield, Virginia 22151 USA, ISBN 0-89208-171-6), p. 283–287.

[14] GSCHWIND (Rudolf) and FREY (Franziska): 1994, "Investigations on the bleaching behaviour and the reconstruction of faded colour prints", *The Journal of Photographic Science*, 41, p. 76.

[15] FREY (Franziska) and GSCHWIND (Rudolf): 1994, "Mathematical bleaching models for photographic three-color materials", *J. of Imaging Science and Technology*, 38 (6), p. 513.

[16] LAVEDRINE (B.), ROBERT (F.) and FLIEDER (F.): 1988, "Evaluation of dark stability of reversal color films using Arrhenius' law", *J. Photogr. Sci.*, 36 (3). p. 68.

[17] *Preservation of Photographs*, Eastman Kodak Company, (1979).

[18] *Storage and care of KODAK Color Material*, Eastman Kodak Company (1982).

[19] *Conservation of Photographs*, Eastman Kodak Company (1985).

[20] ANDERSON (Stanton) and GOETTING (R.): 1988, "Environmental Effects on the Image Stability of Photographic Products", *J. Imaging Technology*, 14, p. 111.

[21] HENDRIKS (K. B.): 1989, "Stability and Preservation of Recorded Images", in *Imaging Processes and Materials* (Nebelettes 8th edition, Van Nostrand, NY), p. 637.

[22] ADELSTEIN (P. Z.): 1991, "International standards on permanence of imaging materials", in *Sauvegarde et conservation des photographies, dessins, imprimés et manuscrits*, Actes des journées internationales d'études de l'ARSAG, Paris, Oct. 1991.

[23] TUITE (R. T.): 1979, "Image Stability in Color Photography", *Journal of Applies photographic engineering*, 5 (4), p. 200.

[24] Eastman Kodak Company, "Restoring faded transparencies by duplication (white light printing methods)", in *Current information summary* (CIS-22), July 1979.

[25] Eastman Kodak Company, "Restoring faded transparencies by duplication (tricolor printing method)", in *Current information summary* (CIS-23), August 1979.

[26] HUNT (C. Bradley): 1981, "Corrective reproduction of faded color motion picture prints", *SMPTE J.*, p. 591–596.

[27] YU (F. T. S.), MU (G. G.) and ZHUANG (S. I.): 1981, "Color restoration of faded color films with white-light processing", *Optik*, 58, p. 380.

[28] GÄL: 1967, *Methodik der Wasserdampfsorptionsmessung* (Springer-Verlag, New York), p. 40.

[29] *ISO-Standard 10977, Photography – Processed photographic colour films and paper prints – Methods for measuring image stability* (First edition 1993–02–01).

[30] Anderson (S.) and Kopperl (D.): 1993, "Limitations of Accelerated Image Stability Testing", *J. Imaging Science and Technology*, 37, p. 363.

[31] Meyer (Armin) and Bermane (D.): 1983, "The Stability and Permanence of Cibachrome Images", *J. Appl. Photogr. Eng.*, 9, p. 121.

[32] Bermane (D.): 1984, "Influence of Azo-Dye Aggregation on the Dark Stability of Cibachrome Images", *J. Imaging Technology*, 11, p. 105.

[33] Williams (F. C.) and Clapper (F. R.): 1953, "Multiple internal reflections in photographic colour prints", *Journal of the Optical Society of America*, 43, p. 595.

[34] Gschwind (R.), Rosselet (A.) and Buser (H. J.): 1993, "Investigation and quantification of inter-image effects", *The Journal of Photographic Science*, 41, p. 86.

[35] Hunt (R. W. G.): 1987, *The Reproduction of Colour in Photography, Printing & Television* (Fountain Press, England), p. 247.

[36] Ohta (N.): 1973, "Estimating Absorption Bands of Component Dyes by Means of Principal Component Analysis", *Anal. Chem.*, 45, p. 553.

[37] Vandenginste (B.) *et al.*: 1985, "Three-Component Curve Resolution in Liquid Chromatography with Multiwavelength Diode Array Detection", *Anal. Chim. Acta*, 173, p. 253.