The long-term development of three-color Kodachrome. An odyssey from the additive to the subtractive method of color reproduction

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ABSTRACT

The introduction of three-color Kodachrome in 1935 was possible thanks to the long collaboration between the independent inventors Leopold Mannes and Leopold Godowsky and the managers of the Kodak Research Laboratory at Rochester, New York. This paper considers this long research work initiated in 1917 by examining the technological solutions Mannes and Godowsky progressively followed, in the historical context of the first cinematographic additive processes. Besides the technological context, the paper analyzes the evolution of Mannes and Godowsky position into Kodak research. Working independently at the beginning, the two young men were funded by their families first, then by the Eastman Kodak Company and Kuhn, Loeb & Co, experimenting in their personal laboratory. In a second step, Mannes and Godowsky were finally employed by Kodak in 1931 as consultant researchers and incorporated with the team of the Kodak Research Laboratory at Rochester. In the mid-1930s Mannes and Godowsky were able to develop a two-color cinematographic process, which finally evolved in the three-color Kodachrome process. This innovative process was announced in April 1935, despite the fact that the Kodak researchers did not succeed in finding a correct developing process for exposed films. An immense amount of work was done in the American laboratory to find a correct sequence of chromogenic development in the summer 1935. This long research odyssey ended when the Kodak research team managed to drastically simplify the developing process of exposed Kodachrome rolls in 1938, encouraged by the recent German competition and the Agfa Color Neu process.

KEYWORDS: Color photography, Kodachrome, Eastman Kodak, additive technology, subtractive technology, industrial research, Kodak Research Laboratory.

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1. Introduction

With the long-term research undertaken by Leopold Mannes and Leopold Godowsky for a three-color multi-layer process, a new form of innovation took place at the Eastman Kodak Company (mentioned below as Kodak). It was the alliance between independent research and the industrial research organization of one of the main film manufacturers of the period. Given the final result of the three-color Kodachrome released in 1935, this scientific collaboration can be judged as a positive, successful one. The Kodachrome was a three-color reversal film which produced a positive image on a transparent base, and which was originally available as a motion picture film and then as a still film. It was the first commercialized color film to use the subtractive method of color reproduction, that involved the selective analysis and absorption by at least three superimposed layers of the red, green and blue components of a filmed subject. Before Kodachrome, the additive method of color reproduction was favored by inventors. Using the theory of the trichromatic color vision of the human eye, this method implied the filming of separation views through at least two colored filters, and the reproduction of the natural colors of the subject in adding the separation films obtained by projecting them through the same filters. The full collaboration necessary for the development of the Kodachrome differed from the model of the lenticular Kodacolor's development, for which patent rights were purchased from a third-party company without a complete sharing of knowledge, and which was introduced in 1928. The lenticular Kodacolor was a three-color motion picture film made of a black and white reversal film coated on an embossed lenticular base, which requested 3 colored filters in red, green and blue during the exposure and the projection. It was quickly replaced by the Kodachrome from 1935 on. The research odyssey of Mannes and Godowsky for the Kodachrome between 1917 and 1935 has already been studied and partially documented by Friedman (1944), Collins (1990), Coote (1993), Brayer (1996) and Le Guern (2017, 2019). This paper will only point out some events and milestones of their research work and clarify how an important teamwork was necessary at Kodak to work out a correct development process in 1935, and to simplify it 3 years later.

2. Early attempts with the additive method of color reproduction

The legend indicating that Kodachrome was invented by two skilled musicians living far from science is wrong. Mannes and Godowsky were talented inventors who used a scientific background to transform the theory into a true process through experimentation. Godowsky studied chemistry, physics and mathematics at the University of California and Columbia University and Mannes received his Bachelor of Science degree in physics from Harvard in 1920 (Brayer, 1996, p.224; George Eastman House, 1964, p.15). The two men had met in high school in 1916 and became friends with a mutual interest in photography. The next year, Mannes and Godowsky saw in New York a film entitled *Our Navy* made with the Prizma I additive process. The color rendering was not good and they started to undertake some research work at their high school to develop a better additive process. Prizma I had been developed by William Van Doren Kelley with the collaboration of Charles Raleigh, one of the inventor of the Kinemacolor process. Briefly, Godowsky remembered in an interview in the 70s that *Our Navy* was a two-color process only. However, this additive process used a rotary filter made of 4 color filters combined in pairs of complementary colors, so we could also see this process as a 4-color one (Dorot Jewish Division, 1971, p.39-40; Layton and Pierce, 2015, p.52-53).

Mannes and Godowsky started by improving a parallax issue encountered with multiple lens systems. The effect of parallax occurred with color additive processes, when the spatial viewpoint of each lens to record a color was slightly offset from the viewpoints of the other lenses. Therefore, the superimposition of the images was not optimal. They continued their research work during their holidays and managed to conceive a viable two-color additive process. It consisted of side-by-side images on a single strip of film exposed in a double-lens prototype camera. An experimental film was made but upon failing to adapt the projection equipment to the two-color film Mannes and Godowsky gave up their first color process (Collins, 1990, p.206). When they graduated from university, they started to work full time as professional musicians but were still experimenting during their spare time on color processes. At the beginning of the 1920s, they progressively turned from the additive to the subtractive theory, considering rightfully that the multi-layer technology could be a better solution than a two-color or three-color additive process to develop a color motion picture film. In their makeshift laboratory at home, they managed to coat double-layered plates able to record part of the visible spectrum (Brayer, 1996, p.225). But they also worked on the theory of three-color photography and filed their first patent application in October 1921, to secure the making of a colored positive from a set of separation negatives (Mannes and Godowsky, 1925; Friedman, 1944, p.108-109).

Evidence of a research work by Mannes and Godowsky on three-color photography has been found by the American artist Matthew Gamber in 2018. Analyzing the industrial archive left by Godowsky at the George Eastman Museum, Gamber found photographic tests dated 1920 made with 3

separation negatives on black and white film using filters. He digitized each separation and combined the 3 files to create a final color photograph using an image processing software (Gamber, 2019). The first photographic result was a view of the Ansonia Hotel in New York from Mannes and Godowsky's apartment, where they installed a personal laboratory. The second image was a portrait of a young lady, identified by Gamber as a cousin-in-law of Mannes, the illustrator Helen Theresa Damrosch Tee-Van, daughter of Frank Damrosch (Fig. 1). This technique of three-color photography reminds us the process used by the Russian photographer Prokudine-Gorski. The knowledge of this research work is useful because it confirms that in 1920, Mannes and Godowsky had not fully decided yet between the additive and the subtractive method of color reproduction.

Fig. 1. Matthew Gamber, three-color separation composite of Helen Damrosch Tee-Van, from a set preserved at the George Eastman Museum of three black and white negatives made by Leopold Godowsky and Leopold Mannes in New York City, NY, circa 1920.

3. The issue of funding and the progressive collaboration with Kodak

In the early 1920s, Mannes and Godowsky faced an important constraint. They had to seek funds to significantly improve their research work and results, as their families decided to stop their financing. In 1922, they were able to meet George Eastman directly to present their work on color photography. Eastman was intrigued by their findings, but the meeting had no financial results (Brayer, 1996, p.225). Finally, the two researchers managed to contact the photochemist Kenneth Mees who was the first director of the Kodak Research department. During one trip to New York, the intrigued Mees met Mannes and Godowsky at the Chemist's Club and was impressed by the progress of their photographic work. From then on and during the following years Mees accepted to supply them with the materials they would need for their research, especially some experimental film coated with more than one emulsion layer on a transparent base, prepared according to their specifications, provided that the two Leopolds would keep him informed of their further developments (James, 1990, p.166; McCarthy, 1987, p.10; Brayer, 1996, p.225). The same year, Mannes had also approached Everett Somers, a secretary of the investment firm of Kuhn, Loeb and Company. The two inventors gave a demonstration of their experimental process and managed to get a twenty thousand dollar loan from the firm (Strauss, 1962, p.97-98).

The money was invested in the research and around one year later, Mannes and Godowsky filed another patent application for a two-color negative process (Mannes and Godowsky, 1924). A red-sensitive emulsion was coated on a transparent support, and an orthochromatic emulsion - blue and green-sensitive - was coated on the red-sensitive emulsion. After development and fixation this multi-layer film was treated with ferricyanide to convert metallic silver into silver ferrocyanide. The new feature of the patent consisted in the method used for the development of the ferrocyanide images: the diffusion into the gelatin of the solution used could be controlled at will. Thus, one could develop only one layer without polluting the other one. Mannes and Godowsky took care not to unveil any formula or detailed mechanisms of this controlled diffusion (Friedman, 1944, p.109-110). In 1925, the independent photochemist Edward J. Wall published his *History of Three-Color Photography* and Mannes and Godowsky knew that they were cited in the book for their 1924 patent (Wall, 1925, p.158). Wall's book was influential, because they learned for the first time the scientific narrative of the monopack film and the potential of color development from the use of color couplers, which were chemical substances able to form dyes (Coote, 1993, p. 139).

From 1925 on, Mannes and Godowsky decided to investigate the chemistry of color couplers and began working on a technology of *integral tripack* or *monopack*, which relates to a reversal multi-layer film made of three inseparable light-sensitive emulsion layers coated one on

the other on a transparent flexible base. One such multi-layer film was different than their initial two-layer negative process, which requested two different toning after the development to form the color in each layer. With Wall's book they read that a young independent photochemist Karl Schinzel was the first to patent the use of a subtractive monopack for color reproduction in 1905. In his process called *Katachromie* Schinzel suggested using a coated plate with several layers of silver bromide emulsion separated by plain gelatin films. Each sensitive layer was colored complementary to its sensitivity. However, this innovative process was theoretical and the few dyes available were not satisfactory to allow its practical use (Coote, 1993, p.134-135; Friedman, 1944). In 1907, Benno Homolka from Hoechst simplified Schinzel's process by inventing the principle of color development. He found that it was possible to form colored images by the creation of dyes in combination with silver images (Coote, 1993, p.135). This discovery was finally patented by Rudolph Fischer and his colleague H. Siegrist in 1912 with their method of color development anticipating the manufacturing of a subtractive tripack. For this process three emulsion layers were also coated on top of one another, and in each layer chemical dye-forming substances called color or dye couplers were incorporated. These dye couplers were supposed to form a dye image together with reduced silver into each emulsion layer in the presence of a developing agent. However, like Schinzel or Homolka, Fischer was unable to realize his process in practice due to its complexity and to the poor stability of the dye-forming substances available in the 1910s. Another issue was the impossibility to prevent the dye couplers from wandering between layers (Coote, 1993, p. 139). From 1927 on, Mannes and Godowsky conceived a different strategy for the color development to get around this problem. Unlike other methods, they decided to include the dye couplers into the liquid developer instead of each emulsion layer. Thus, the wandering coupler problem would be solved, but not the similar issue of the wandering sensitizing dyes (James, 1990, p.166; Collins, 1990, p.211).

In 1928, the chemist of the Kodak synthetic chemistry division Leslie Brooker was able to synthesize new dyes, which were excellent sensitizers from Frances Hamer's research work (Mees, 1961, p.121-123). The problem of wandering sensitizers was almost solved. The pooling of Mannes, Godowsky and Brooker's research works eventually constituted innovation because from that stage the monopack concept could move from theory to practice. For Mees, the time to increase the scientific collaboration with Mannes and Godowsky had come:

> In 1930, I realized that the new dyes that we could now make would solve the problem of making Mannes' and Godowsky's proposed color process work. […] So we asked Mannes and Godowsky to join us here, where they worked happily with us for ten years, and we all set to work and made the new color process work (Mees, 1955, p. 37).

The agreement seemed an easy one. Kodak offered to pay a lump sum of $30,000, annual salaries of $7,500 each and also agreed that Mannes and Godowsky would receive royalties on all patents filed before the collaboration with Kodak (Coote, 1993, p.139; Collins, 1990, p.211). The two independent researchers accepted the offer and became incorporated in the Kodak research organization in November 1930. First, they worked in a special laboratory at New York. After 1 June 1931, they started working at Kodak Park in Rochester (Kodak, 1930, p.4).

Finally employed by Kodak, Mannes and Godowsky had to adapt their research methods to the collaborative work with the Kodak Research Laboratory's staff, because they were also known as professional musicians and had to prove their skills in photochemistry at the same time (Kodak, 1989, p.51). However, this period is not well documented and it is difficult to ascertain the research work done and the practical terms of the collaboration. From 1930 on, the two inventors focused on processes involving mono-layer and mixed grain coatings to avoid the use of a multi-layer coating and its potential problems (Coote, 1993, p.140). As Mannes and Godowsky had a three-year contract terminating at the end of 1933, and as the results of their research were not visible enough, Mees had to insist with members of Kodak management that they should be given another chance for one more year. They finally developed a concrete two-color motion picture film in 1934, "working practically around the clock, day after day" (James, 1990, p.166-167). As the production of the new film was delayed due to some complications, Mannes and Godowsky were able to perform additional research and modified the two-color into a three-color process.

4. Market launch of a three-color film not yet finalized in 1935

Finally, the new Kodachrome process in its 16mm version for color movie was announced in April 1935. As the motion picture film consisted of five layers of emulsion and gelatin it was nicknamed the "quintuplet" film by Science magazine (Anon, 1935). Three layers were devoted to the recording of the blue, green and red spectrums. Between each sensitive layer a thin layer of clear gelatin was coated, used as a margin of safety during the development process and the use of the controlled diffusion bleach (Fig. 2). It was thus possible to bleach two layers and not the

bottom layer. Nevertheless, the first development process was very long and involved in all 28 steps (Coote, 1993, p.142; Coe, 1978, p.128).

However, the correct development processing for the new Kodachrome film was not at all ready in April 1935. This situation was critical. It was possible to expose some 16mm Kodachrome reels but it was still impossible to get a neutral colorimetric rendering of the developed slides. Mees had to organize and supervise an exceptional program in extreme circumstances; the theoretical technology of Kodachrome had to confront the practical side of the laboratory (Le Guern, 2017, p.264-265).

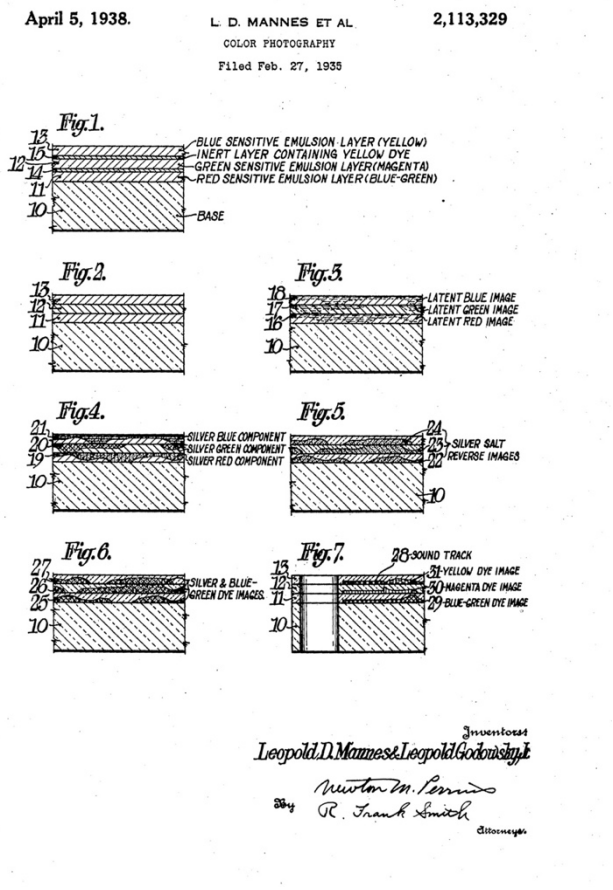

Fig. 2. Drawings from the American patent US 2113329A « Color photography » filed by Mannes and Godowsky on 27 February 1935 and granted on 5 April 1938 (Espacenet, European Patent Office).

In one of his notebooks, the researcher Franck B. Phillips detailed this critical period of intense research for a satisfactory development process. Phillips, a member of the Harrow Research Laboratory, was already visiting and working at Rochester in November 1934. He had probably been requested to help the American scientists and assist Mannes and Godowsky. In April and May 1935, he was testifying to the intensive work undertaken in the Research Laboratories. The teams were working nearly all day long with infrequent breaks in a desperate quest for better Kodachrome processing (Phillips, 1935). On May 10th, Phillips noted that “a man (Pringle) was sent to the Medical Dept having been made sick with fumes from acetone-alcohol mixture while cleaning racks from the b-g developer” (Phillips, 1935, p.71). One day, Phillips reported that the general tendency of the experimental work was the development of Kodachrome with green neutrals. The photochemists tested several solutions to reduce the color cast but, as the writer noted, the "results were very erratic" (14 May 1935, p.75). Some days later, the situation was better and the developed Kodachrome motion picture films at last reached a correct neutrality in the grey. The magenta bleach had been acidified with hydrochloric acid to reduce the residual blue-green dye. This acidification was criticized by Godowsky but Phillips disagreed in his notebook (Phillips, 1935, p.79). This evidence of research teamwork illustrates well the complexity of the new Kodachrome process.

5. Chemical stability and color rendition of three -color Kodachrome version 1935-1938

Regarding this first version of Kodachrome film, it is challenging to estimate their photographic characteristic such as color rendition or stability of dyes owing to their scarcity in the early 2020s (Fig. 3). Sylvie Pénichon recently pointed out that original Kodachrome transparencies should not be projected due to their poor stability to light (Pénichon, 2013, p.204). Louis W. Sipley, a photographer and the creator of the American Museum of Photography in Philadelphia, included in his 1951 book valuable information about the stability of Kodachrome:

The dyes in this earliest Kodachromes were not very stable, with the result that pictures made on the 1935 film have degraded and no longer retain the full colors as originally made. Just as this book go to press [so we were in 1951] the American Museum of Photography has been presented with several rolls of 16mm Kodachrome motion pictures made in 1935 which show almost monochromatic pictures of a purple-magenta character (Sipley, 1951, p.142).

This clue points out that the yellow and cyan dyes in particular were less stable in the Kodachrome sandwich made and developed in 1935. Motion picture and still film rolls in color made during the period 1935-1938 are really rare or difficult to identify in the institutions preserving film heritage such as national or private archives and museums.

Fig. 3. The first version of three-color Kodachrome was introduced in 1935 as a 16mm movie film, and as a 35mm film for still cameras in 1936 (Eastman Kodak Company, 1971, p. 13).

However, a short film made in 1937 by the well-known photographer Man Ray provides some information about the nature of Kodachrome color rendering. According to Man Ray, he received a large quantity of Kodachrome rolls to test and a 16mm camera from the British subsidiary of Kodak in London (Man Ray, 1963, p.293-294). The result was a short film named “La Garoupe”, more than 10’ long, some portions of which were recently shown in a French documentary named “Un été à la Garoupe” (Knowles, 2012, p.239-240; Lévy-Kuentz, 2020).

The competition with Kodachrome was tough. In 1936, the I.G. Farbenindustrie A.G. at Wolfen in Germany managed to develop a technology of anchoring color couplers to individual emulsion layers, with the use of long-chain molecular structures. This way, a process of selective color development by controlled diffusion used by Mannes and Godowsky, was no longer necessary. The color couplers could be incorporated into the monopack film, and not during the developing process of the exposed film. Finally, after a satisfying selection of couplers for each of the three layers, Agfa introduced in October 1936 the Agfacolor Neu film including a simplified multi-layer reversal technology (Flueckiger, 2012). This innovation into the field of the monopack film led Mannes, Godowsky and their colleagues at the Kodak Research Laboratories to optimize the Kodachrome process.

6. The necessary simplification of the three-color Kodachrome developing process

For Kodak, the elegant solution of the Agfacolor Neu was a technological and economical threat even if the color rendering of the Kodachrome film was slightly better. The technology used by Agfa was far simpler and rendered the 28 steps necessary to the processing of Kodachrome films obsolete. The need of improving the stability of the chemical dyes used in the layers of Kodachrome was another important fact. Kodak’s first action was to develop a simpler processing for the Kodachrome films. It was not before 1938 that they released this new processing. The controlled diffusion bleach was replaced with selective re-exposure for each color-development step. In this way the total number of steps was reduced to 18 (Kodak, 1989, p.52).

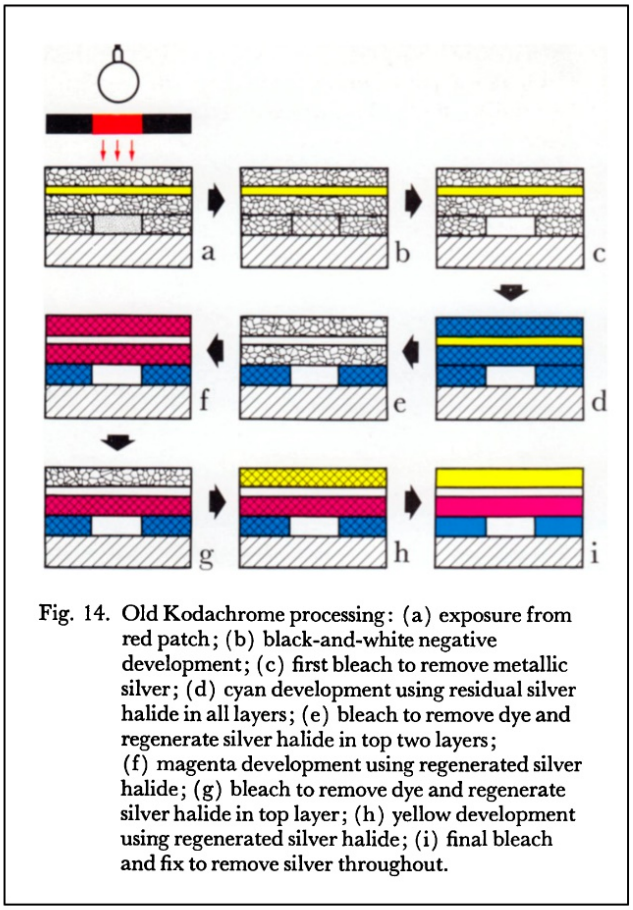

Fig. 14. Old Kodachrome processing: (a) exposure from red patch; (b) black-and-white negative development; (c) first bleach to remove metallic silver; (d) cyan development using residual silver halide in all layers; (e) bleach to remove dye and regenerate silver halide in top two layers; (f) magenta development using regenerated silver halide; (g) bleach to remove dye and regenerate silver halide in top layer; (h) yellow development using regenerated silver halide; (i) final bleach and fix to remove silver throughout.

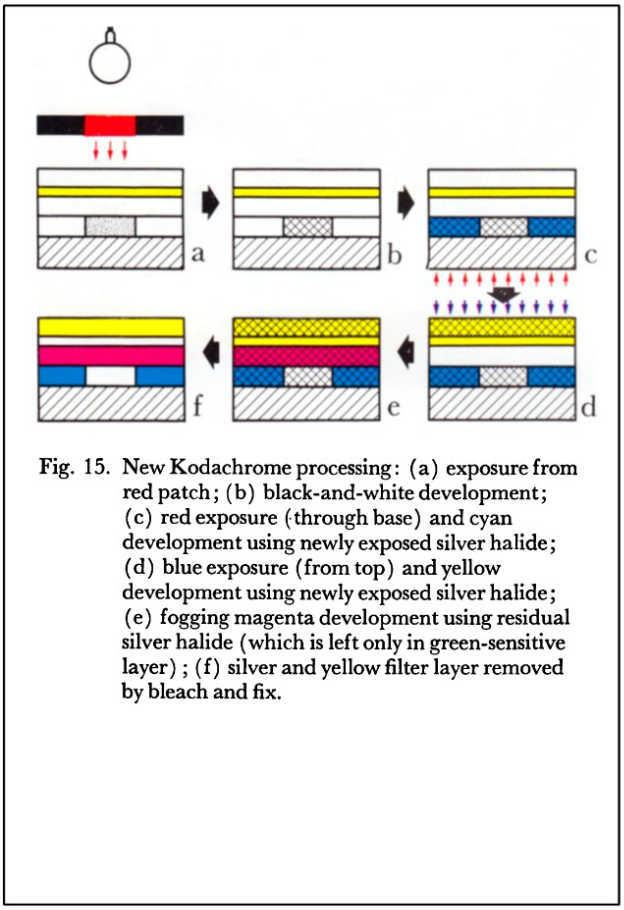

Fig. 15. New Kodachrome processing: (a) exposure from red patch; (b) black-and-white development; (c) red exposure (through base) and cyan development using newly exposed silver halide; (d) blue exposure (from top) and yellow development using newly exposed silver halide; (e) fogging magenta development using residual silver halide (which is left only in green-sensitive layer); (f) silver and yellow filter layer removed by bleach and fix.

Fig. 4. First Kodachrome developing process (1935-1938) compared with new Kodachrome developing process (from 1938) in Weissberger (1970).

Lot Spaulding Wilder, a researcher of the Rochester Laboratory, was the inventor of the Kodachrome processing simplification (James, 1990, p.169). After the release of the Kodachrome monopack, Mees decided to create an experimental department for color photography including Wilder, Ralph M. Evans and Wesley T. Hanson. Mannes and Godowsky also played an important role for scientific and patent work during the period up to the outbreak of the Second World War.

The final process was described by Friedman (1944, p.122). The new processing was equivalent up to the exposure with red light and the development in cyan developer (Fig. 4). The next step was to expose the blue sensitive layer from the top of the film with a blue light, and to develop with a yellow-coupler developer. Then the middle layer magenta sensitive was exposed to white light or treated by a fogging agent such as methylene blue or thiourea. This layer was developed with a magenta-coupler developer and the rest of the processing was similar to Wilder's experimental process of February 1938. The move from theory to production was unsurprisingly tough, as confirmed by Mees in 1944:

This process offered very considerable difficulties when it was first attempted but, in view of its advantages, they were overcome, and it is the method by which the Kodachrome film is now processed (Mees, 1944, p.234).

Following the successful simplification of the Kodachrome developing process, Mannes ceased his collaboration with Kodak in 1939. The same year, Godowsky left the Kodak Research Laboratory but still worked on color photography as a consultant in a small personal laboratory in Westport, Connecticut, nicknamed "Kodak Park Westport" (Kodak, 1989, p.54). After the Second World War, the knowledge produced and mastered on color technology would lead to other Kodak processes, such as Kodacolor negative film, Ektachrome reversal film and Eastman Color Negative.

7. Conclusion

This paper attempted to outline how the introduction of the 16mm version of Kodachrome in 1935 was only the beginning of Kodak research on color technology. It was only made possible with the long-term collaborative work

with the atypical photochemists Mannes and Godowsky and the researchers of the Kodak Research Laboratories. In 1917, Mannes and Godowsky began studying independently the technology of color additive processes in the quest for a motion picture film in color. In the early 1920s, they managed to create a scientific collaboration with Kodak and be funded by Kuhn, Loeb and Company. Mannes and Godowsky gave up the additive method and investigated the concept of subtractive multi-layer film involving a color development from 1925 on. They were employed by Kodak and incorporated in the Research Laboratories in 1931, and managed to develop the three-color Kodachrome, a motion picture film in 1935. The introduction by Agfa of the three-color Agfacolor Neu film led Mannes, Godowsky and the Kodak researchers to simplify the Kodachrome developing process in 1938.

8. Conflict of interest declaration

The author declares that there is no conflict of interest related to this publication. There are no actual or potential conflicts of interest, including financial, personal or other relationships with other people or organizations.

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11. Short biography of the author

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