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AN INFRARED SENSING TECHNIQUE FOR REAL-TIME MACHINE PROCESS CONTROL

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A process control technique is described wherein a direct assessment of the camera film being processed is made using an infrared densitometer to monitor the density of a calibrated exposure on the developing film. Using a device which embodies this technique, it was demonstrated that substantial variations in developer temperature, concentration, and exhaustion could be tolerated; standard-equivalent sensitometry was obtained in the presence of the developer variations described by an appropriate adjustment of development time, which was indicated by the device read-out.

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1. INTRODUCTION

The purpose of any process control scheme is to achieve the continuing and repeatable production of an item within some defined limits of quality. For effective process control it is necessary to (1) assess process performance with respect to a standard, and (2) control those stages of the process which are critical to product quality. When processing photographic materials, the desired end product is a high-quality image. In general, but especially when processing black-and-white negative materials, the critical process step is the developer; it is in the developer that the silver halide emulsion is reduced to a metallic silver which forms the image. It is not surprising, therefore, that the chemical activity of the developer is of great importance in photographic process control and that considerable effort is expended to maintain developer activity at a specified level.

To assess developer activity, there are, in general, two techniques: (1) Sensitometric, wherein a sensitometrically exposed control strip is carefully processed for a specified time/temperature, and developer activity is inferred through comparing the resulting control strip densities to a standard, and (2) Chemical, wherein the activity of the developer is determined by chemical analyses which measure those factors which most affect it, e. g., pH, developer concentration and halide concentration. Replenisher addition and close control of the developer temperature are typical measures which are intended to maintain a desired level of developer activity. A densitometer, a supply of relatively expensive control strips, and a freezer for stable control strip storage are basic requirements for the sensitometric method, while chemical analyses ordinarily require a pH meter, reagent grade chemicals, and assorted laboratory glassware, although some automatic analytical systems are available. Either method requires specialized operator training and considerable experience if maximum benefit is to be realized. Although the sensitometric technique is probably more widely employed, both methods are well-proven and are commonly accepted in the photographic processing industry. With careful utilization and proper data interpretation these techniques ordinarily ensure a high quality product. They have the additional advantage of accumulating quantitative data which provide an historical record that is potentially useful in maintenance and repair scheduling, process evaluation and modification or, perhaps, personnel evaluation.

As mentioned above, these methods attempt to control the variables which affect developer activity, and to maintain them within specified tolerances. Generally, however, any quantitative relationship between camera film and the chemistry is ignored, although it is common practice to inspect visually the finished work. Furthermore, there are those out-of-control conditions which cannot be handled satisfactorily by manipulating replenishment rate and temperature; faced with this situation, the common answer is to dump the offending solutions and start afresh. This procedure is not only time consuming, but it places an additional burden on logistic channels.

These standard process control techniques were considered for use in the ES-38B(1) Mobile Photographic Darkroom used by the US Army, but were found to be not suitable for that application because of their dependence on bulky and sensitive equipment and the requirement for a high degree of operator training, together with the problems in the management of out-of-control conditions in a field environment.

2. THEORY/APPROACH

From the observations and concepts outlined above, it was clear that, to implement process control in the ES-38B(1), a technique would be required which objectively determined optimum processing from the camera film being processed, which added little in the way of bulky or sensitive equipment, and which required minimal additional training to operate.

From experience with the familiar time/temperature tables, it is well known that sensitometry equivalent to that produced with "standard" conditions can be achieved, albeit somewhat tediously, when the developer temperature is changed. It was reasoned that, if the several densities of a conventional characteristic curve could be duplicated with appropriate combinations of development times and temperatures, it might be reasonable to monitor one density only, and use that as an index of development.

In a continuous roll film processor, such as the EH-29B, the density measurement could be accomplished at almost any point in the process, but the location of choice is in the development stage so as to minimize the delay between density measurement and corrective action. In the developer, light-sensitive silver halide is still present in the emulsion along with the reduced metallic silver, which leads to the choice of infrared radiation for the task of densitometry.

Spectral data for panchromatic aerial films having extended red sensitivity show negligible response beyond about 725 - 750 nm, and spectral transmission measurements, made on typical system components, e.g., developers, film bases, emulsions containing both silver halide and metallic silver, showed no transmission or absorption peaks to about 1 micron. This left the region between 800 and 1000 nm, where, conveniently, moderately priced solid state sources and detectors are available, having sufficient power and sensitivity.

3. DESIGN OF THE INFRARED DENSITOMETER

Once the approach was determined, a breadboard processor model was constructed to demonstrate the feasibility of the technique. Several evolutionary changes were made, but throughout, the essential aspects of the model were retained which was composed of three component assemblies: (1) Processing Drum, (2) Solution Tank, and (3) Infrared Densitometer. The processing drum to which the film samples were attached was rotated about its horizontal axis by a small DC motor at approximately 6 rpm. Earlier versions of the drum were constructed of transparent tubing (lucite, glass) but the latest version was fabricated from fiberglass tubing, with a cut-out sector, or window, over which the monitored film strip was placed. The solution tank was an open-topped box, with notches (or slots) in the ends to accommodate the axle of the processing drum. It was found that, when processing at temperatures above

$90^{o}F$ a substantial heat loss occurred, and a hinged top was fitted which satisfactorily reduced this loss. The IR Densitometer consisted of a source, a detector, and the electronics package. Originally, a filtered tungsten lamp was used as the source; this was a 12-volt bulb operated at 10 volts. Energy output and operating life were both adequate; however, other considerations dictated a more efficient source, and a Gallium Arsenide Light Emitting Diode (LED) was selected.

Under the conditions of test, the available photo-voltaic or photo-resistive devices used as detectors did not appear to provide sufficient sensitivity over the film density range studied. With successive generations of design an infrared-sensitive photo transistor was chosen for a detector which is an excellent match for the spectral output of the GAs emitter.

The electronic circuitry was successfully configured in two versions. In both designs the developing film passes through the beam between source and detector, and attenuates the radiation to the detector. In the first version an audible signal was sounded when the appropriate density was reached. This was a satisfactory scheme for use when the processor model simulated conventional manual processing, where development would be monitored from the beginning, and where the density being scanned always was seen growing from some low value. In a continuous processor, however, the film would be monitored at one point only as it passes through the developer; this necessitates having the ability to instantaneously determine overdevelopment as well as underdevelopment, since it is possible for conditions to exist such that either can occur. The Block Diagram (Figure 1) shows the present configuration. The Process Standard Selector (PSS) is a ten-turn potentiometer which regulates the output of the LED; it is fitted with a turns-counting dial to permit repeatable settings to be made. The Development Status Indicator (DSI) is a center-zero milliameter. The circuit is designed so that only one level of radiation at the detector will produce a nulling current in the meter, and center the needle. More or less radiation (transmitted through a low or high density in the film being monitored) is indicated by a corresponding needle deflection to the right or the left of zero. For use with the processor model, the LED and photo transistor were mounted on a rigid bracket, opposing each other such that the cut-away sector of the drum, over which the exposed film was located, swept the beam path between them. A sketch of the processor model is shown in Figure 2. When later adapted to a 5A-N Versamat, the LED and photo transistor were mounted externally on the outer housing of the processor and flexible fiber optics were used to go to and from the film.

4. EXPERIMENTAL PROCEDURES

a. Calibration Run:

For each film, a calibration run was made to determine the PSS setting for that film, according to the procedure given below:

(1) Standard processing conditions of development time and temperature are defined for a sample film such that the film so processed yields the desired sensitometric results. These defined conditions may be derived from

manufacturer's instructions or experimental determinations.

(2) Strips of the sample film are exposed using an EG&G Mk VI Sensitometer. One strip is given a uniform exposure; this strip is attached to the drum emulsion out, with the exposed area located over the cut-out window. A second strip is given a conventional modulated exposure, and is also attached to the drum.

(3) When the developer is at the appropriate temperature, the drum, carrying the exposed film, is placed in the tank containing the developer. The drum motor is started, and the development proceeds for the desired time.

(4) At the end of the development time, with the uniformly exposed strip in the beam path, the PSS potentiometer is adjusted until the DSI meter is centered. The film is fixed and washed conventionally in tanks placed close to the drum processor.

b. Test Run:

The developer activity is then modified as desired, the temperature may be changed, the solution diluted or exhausted, etc., and the procedure outlined above is again followed, except that development is allowed to proceed only until the DSI meter has centered, indicating that the density of the uniformly exposed test strip is the same as it was under the standard conditions. This new development time is then noted.

The exposure required to produce the uniformly exposed "control" area is not extremely critical, although, of course, it varies according to the sensitivity of the film being tested. Since a single density was being monitored as an index of the useful characteristic curve, it was reasoned that the control area density should not be so low as to be lost in any expected fog density, nor should it be so high as to require potentially noisy high amplification. For most of the experimental work described herein, it was found convenient to choose an exposure such that, for the film being tested, the resulting density fell in the upper toe or lower straight line of the characteristic curve - roughly, between .70 and 1.10 density.

5. DEVELOPER ACTIVITY VARIATIONS

Using the procedure outlined above, experiments were performed to determine the feasibility of using the technique to correct for:

(a) Variations in developer temperature

(b) Exhaustion of the developer

(c) Dilution of the developer

a. Temperature:

During the course of the present investigation a concurrent subtask was in progress, the objective of which was to develop time/temperature tables for manual processing. These tables were to contain processing information covering the range of still-camera continuous-tone black-and-white films generally available to US Army photographers, manually processed in Armed Forces Developers (AFD) #2 and #3. AFD #2 and AFD #3 are, by specification, intended to be equivalent to Eastman Kodak published formulas for DK-50 and D-76, respectively.

The standard procedure in this sort of determination is an iterative one; a sample of film is developed under standard conditions - in this instance according to recommendations of the manufacturer - and a standard characteristic curve is derived. More samples are then manually developed in the appropriate Armed Forces Developer for a range of development times bracketing the estimated correct time. Sensitometry derived from these trials are compared to the standard, and the process is repeated until the desired curve matching is obtained. This procedure must be repeated for each development temperature of interest. It can be seen that the procedure is quite lengthy, although the desired information can eventually be obtained.

The infrared densitometric technique was applied in this instance to gather the desired time/temperature information, while reducing the number of iterations usually required. The testing procedure outlined earlier using the processor model was followed; standard conditions were those specified by the film manufacturer (developer, solution temperature, development time), and the DSI was set to show end-of-development at the end of this standard time. With the same DSI setting, another sample of the subject film was allowed to develop in the appropriate Armed Forces Developer at the desired temperature until end-of-development was indicated. Additional samples were developed in the Armed Forces Developer at different temperatures (typically 68°F (or 70°F), 75°F and 80°F). Figures 3 through 8 show sets of characteristic curves generated during this phase. It can be seen that, in general, a good match exists among the curves for each film when the standard and test developers are similar. Two exceptions to this are shown in Figures 9 and 10; these represent GAF films for which the standard developer was Hyfinol, a proprietary developer manufactured by GAF, and the test developer was AFD #2. From these curves it can be seen that the samples developed in AFD #2 are consistent inter se, but do not match the Hyfinol-developed standard, even though end-of-development was indicated. It is believed that for these films at least, and perhaps others, there is a difference in infrared transmission which is associated with this type of developer.

Machine process control was also studied. Figure 11 shows the characteristic curves of Eastman Kodak 2420 film developed in Eastman Kodak 641 Developer, using a 5A-N Versamat. Standard conditions were defined as 85°F and a processing rate of 6 ft/min. To simulate process failure, the developer was allowed to cool to 73°F (ambient), at which temperature it was found necessary to reduce the through-put rate to 2.9 ft/min. to center the needle on the Development Status Indicator meter.

b. Exhaustion:

A one-liter volume of Eastman Kodak D-76 developer was exhausted by processing completely fogged film in increments of 440 square inches (4 full 70mm Nikor reels). Sensitometric tests were conducted using Eastman Kodak Type 3401 film, samples of which were processed after each increment of exhaustion. Standard processing conditions were defined at 9½ minutes at 70°F and the DSI was adjusted for these development conditions. A sensitometric strip and control patch were processed, with the development terminated when complete development was indicated by the IR densitometer. Figure 12 shows characteristic curves from samples of film developed in the developer (a) when fresh; and (b) after 1760 square inches of film had been developed therein (4 exhaustion increments). Development times increased from the 9½ minutes in fresh developer to 23 minutes for the exhausted solution.

c. Dilution:

Using the processor model, the Development Status Indicator was set for the standard condition when Tri-X Pan Film was developed in D-76 developer (full strength) at 70°F for 7 minutes. Subsequent runs were made, using developer diluted to ½ strength and 1/3 strength. Development was allowed to proceed until completion was indicated by the DSI. The development times were 10½ minutes and 12¼ minutes, respectively, for the dilutions shown. The characteristic curves for these are shown in Figure 13.

6. ADDITIONAL INVESTIGATIONS

The method was also applied to conditions of known film underexposure and to control color negative development with temperature changes.

a. Underexposure:

It must be noted in the outset that, fundamentally, normal negatives are the result of correct exposure and processing, and that extending the time of development to compensate for a reduction in exposure will result in a negative different from normal. Sensitometrically, the result is higher contrast (increased Gamma) and higher fog. Nevertheless, it is sometimes required to process camera film that has been exposed less than normal, and it is, therefore, of some interest to be able to determine quantitatively an appropriate development time for film so exposed.

To test for underexposure correction, the following procedure was established: A sensitometric strip, control patch and camera negatives were exposed and processed normally on the processor model. At the end of the development time, the DSI was adjusted to show end-of-development. A second series of sensitometric strip, control patch and camera negatives was given half-normal exposures (one step under exposure), and developed until the underexposed control patch reached the density of the normally exposed control patch (which was read out on the DSI).

Compensation for ½ normal exposure required an increase in development time of approximately 75%; as expected, fog and contrast were higher than found with normal development. Characteristic curves from these runs are shown in Figure 14. Qualitative visual examination of negatives corroborated the test results.

Since this method of compensation for underexposure depends on underexposing the process control patch the same amount as the camera film, it will be effective only if the fraction of normal exposure is known quantitatively.

b. Color Processing:

Eastman Kodak Ektacolor S was processed using ECOM Rapid Access Color (RAC) chemistry.[1] At the standard temperature of 75°F the DSI was nulled to indicate development completion after the standard development time of 5 minutes. The test developer temperature was then reduced to 70°F and development was allowed to proceed until completion was indicated by the DSI which occurred at 7 minutes. The time/temperature data obtained on the test drum was then used for conventional manual processing of both camera negatives and sensitometric strips; Figure 15 shows the manually processed characteristic curves from the 75°F, 5 minute standard development time and from the 70°F, 7 minute development time determined by the IR densitometer. Essentially, the red-record emulsion only was monitored for these tests, with exposure to the blue and green sensitive emulsions attenuated by two Eastman Kodak Wratten Filters No. 40R, a total of 80R. It should be noted that this aspect of the feasibility tests was necessarily limited, since color process control was not included in the program objective.

7. CONCLUSION

The successful results of the ECOM Research and Development program demonstrated that the infrared sensitometric control technique described is capable of monitoring the development process to the degree that standard-equivalent sensitometry can be achieved from a variety of non-standard developing conditions.

The process control technique described is suitable for Army field operations and can ensure high-quality aerial negatives over a wide range of less-than-ideal conditions of developer temperature and exhaustion.

[1] Levy, M., and Willey, H; A Rapid Color Negative Processing System; R & D Technical Report, ECOM 4089, March 1973

The technique, and equipment developed for its utilization, is readily adaptable for automatic machine process control by having the monitor head at the mid-point or exit of the developer tank and having some "signal" output control the machine speed to produce optimum process results.

The technique has been successfully used to establish manual processing time and temperature data that vary from standard published data and to establish accurate time/temperature data of films developed in similar developer formulations.

When developer formulas are significantly different, equivalent sensitometric results were not obtained. This is apparently the result of differences in total infrared absorption of the developed silver in the two instances. In the primary application of the present technique, i. e., that of controlling processing in a given developer, one should not experience the problem of cross-developer differences.

The preliminary work described in color process control did establish the feasibility of using the basic technique to monitor color processing. This aspect should be investigated further and the technique developed for Army use.

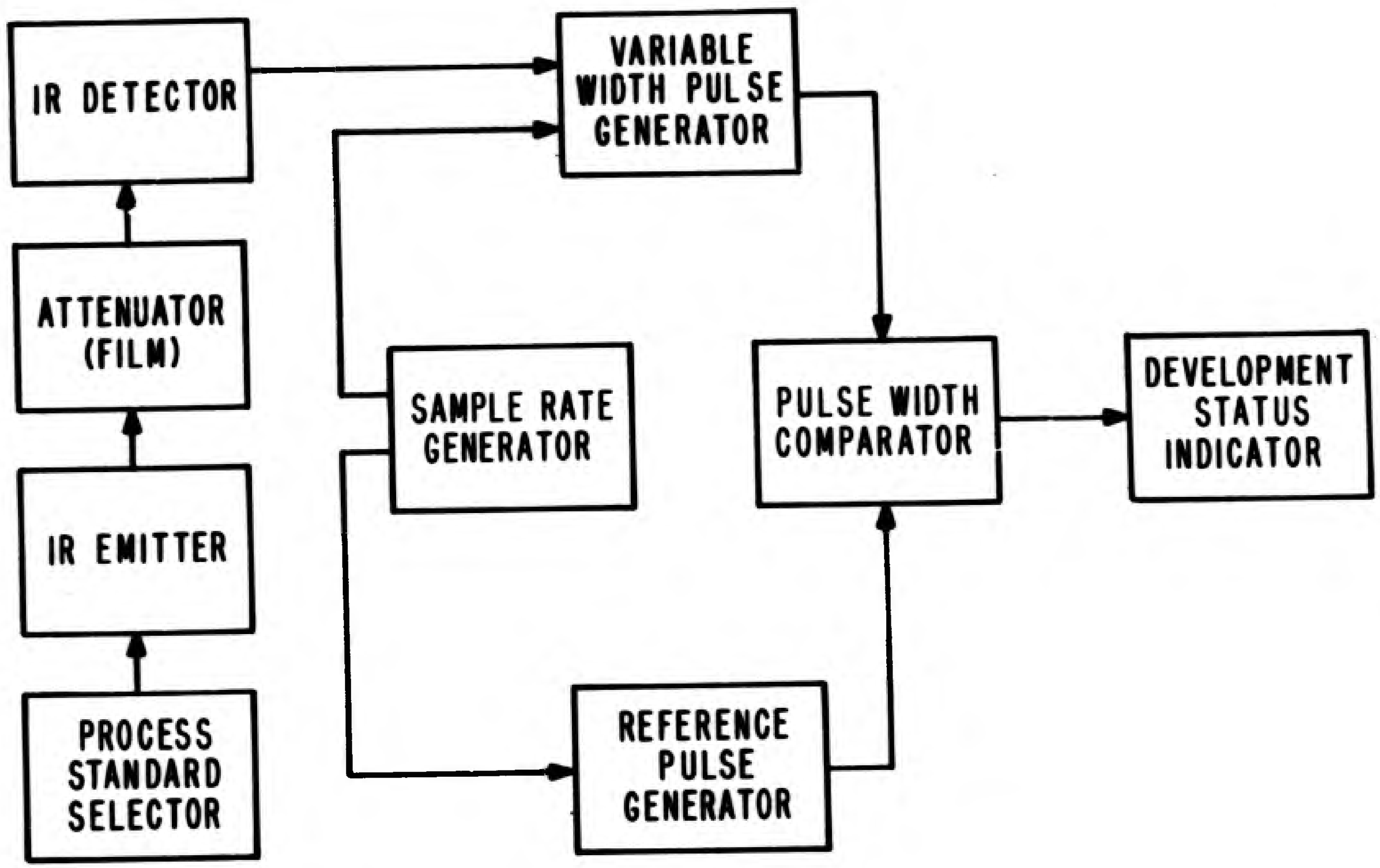
8. RECOMMENDATIONS

It is recommended that the techniques developed under this program be included in the design specifications for the Tactical Image Processing Laboratory, which program is under consideration by AMC.

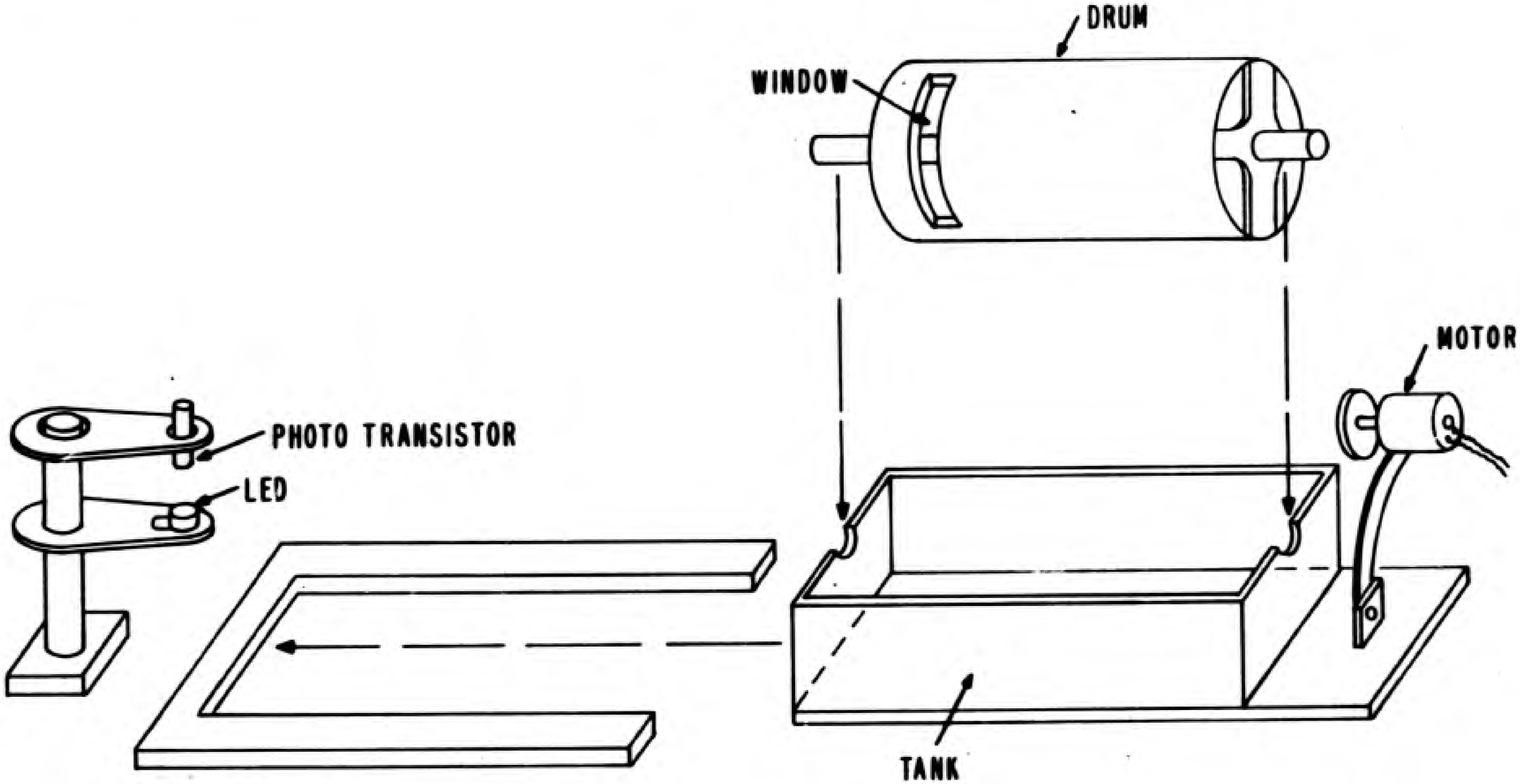
This technique is considered suitable for application in the ES-82 Mobile Darkroom for manual black-and-white processing. Adaptions of the technique discussed can also be used for equipment designed to assist the post-camp and station photographer in his darkroom processing operations.

The technique/and modifications thereof can be used to provide sensitometrically equivalent processed negatives from materials exposed in different locations under different conditions. The technique is adaptable to motion picture processing equipment and will keep reel-to-reel process uniformity optimized.

It is further recommended that a program be established to study this technique or refinements thereof in connection with quality control for automatic machine color processing.

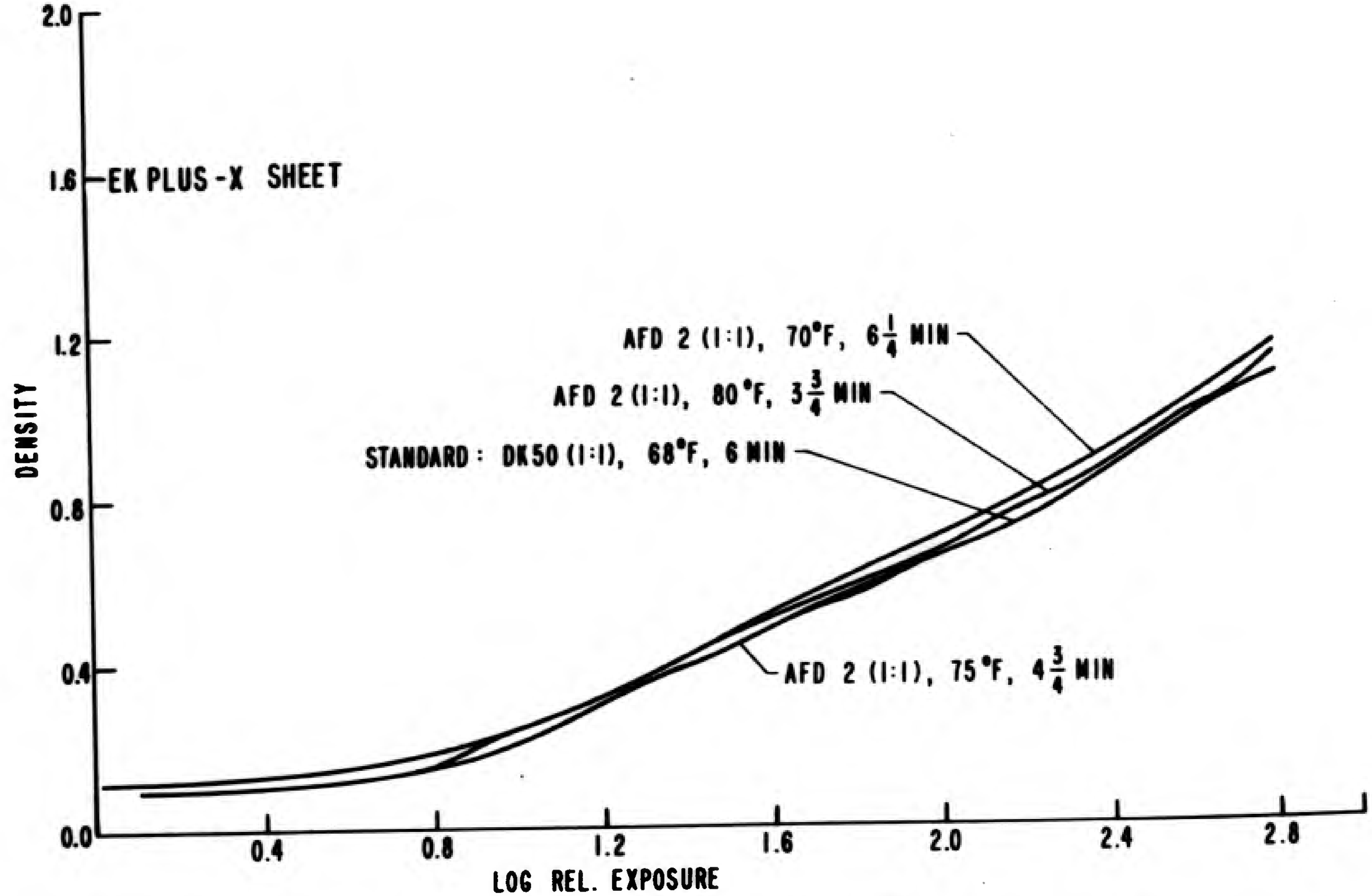


BLOCK DIAGRAM
INFRARED DENSITOMETER
FIG. 1



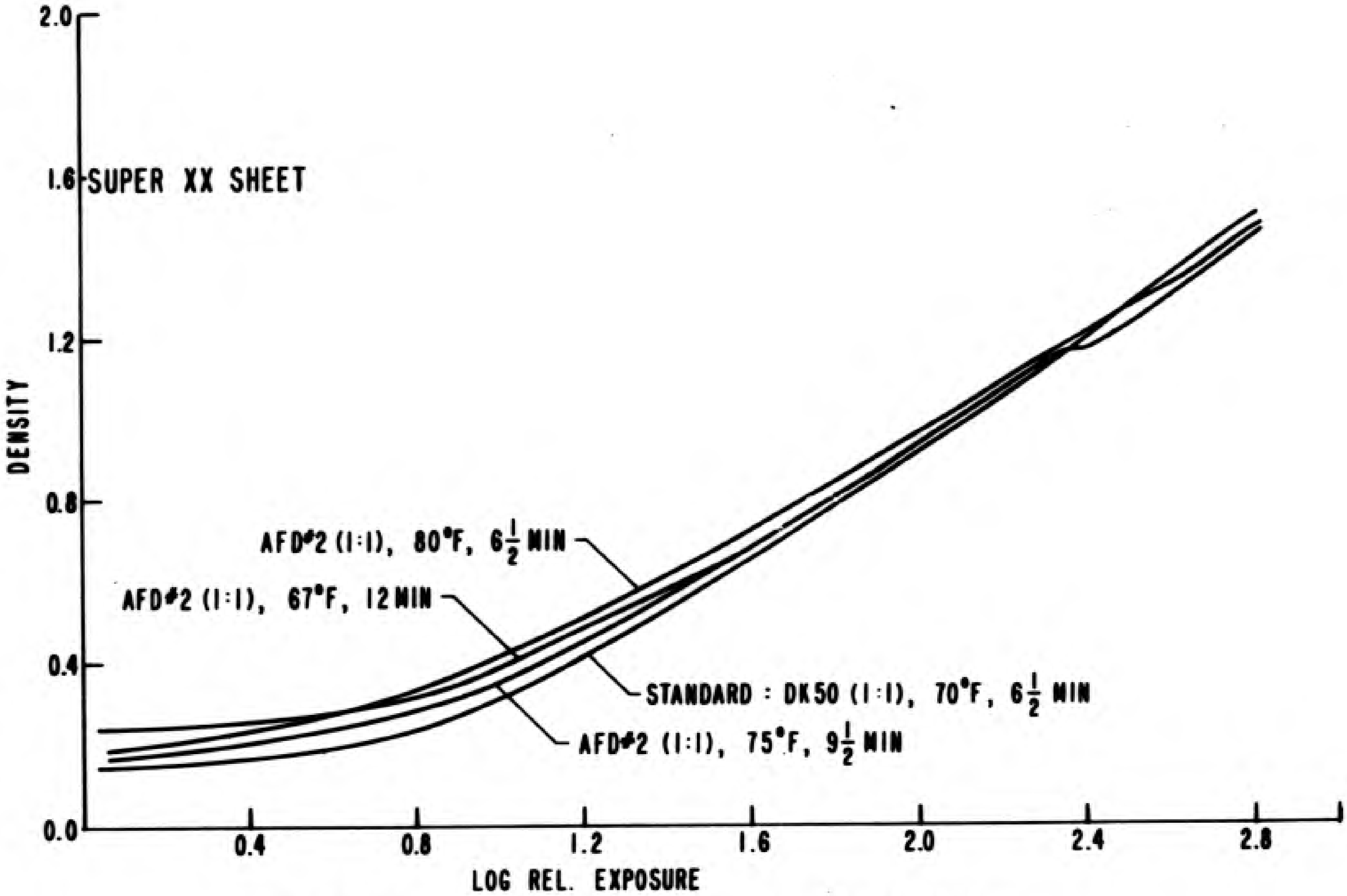
BREADBOARD PROCESSOR MODEL

FIG. 2



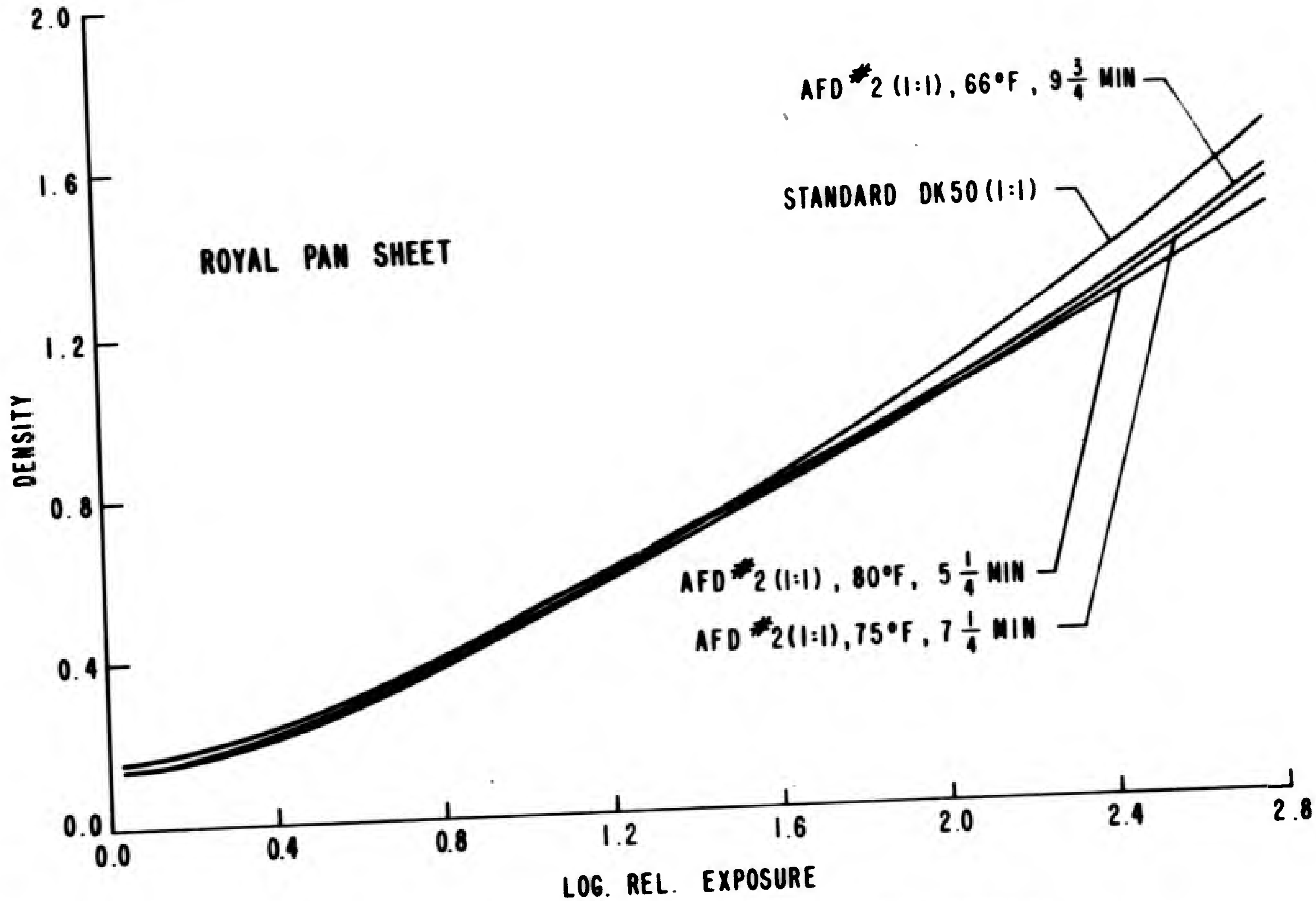
TIME/TEMP DETERMINATION FOR MANUAL PROCESS

FIG. 3



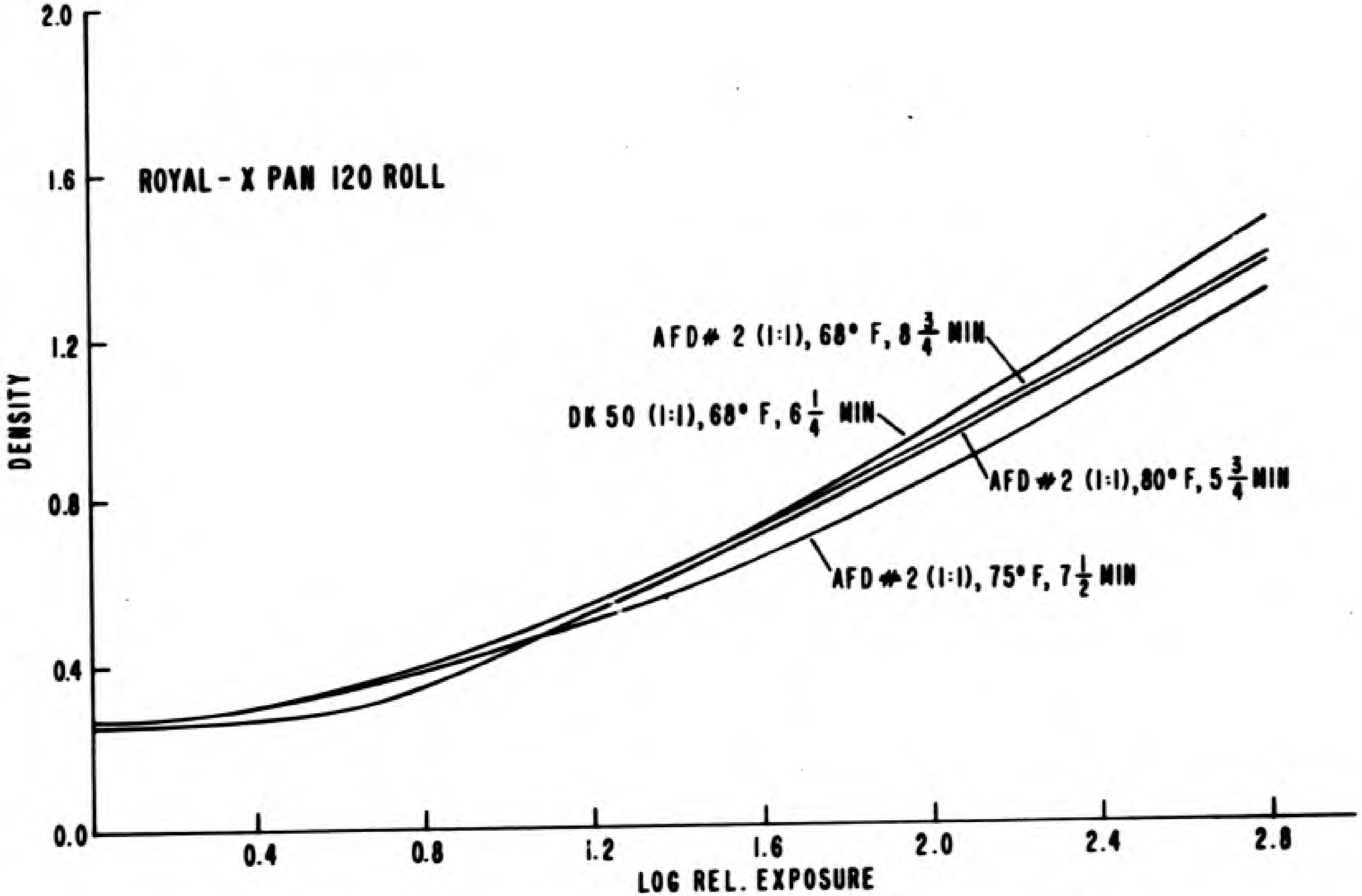
TIME/TEMP DETERMINATION FOR MANUAL PROCESS

FIG. 4



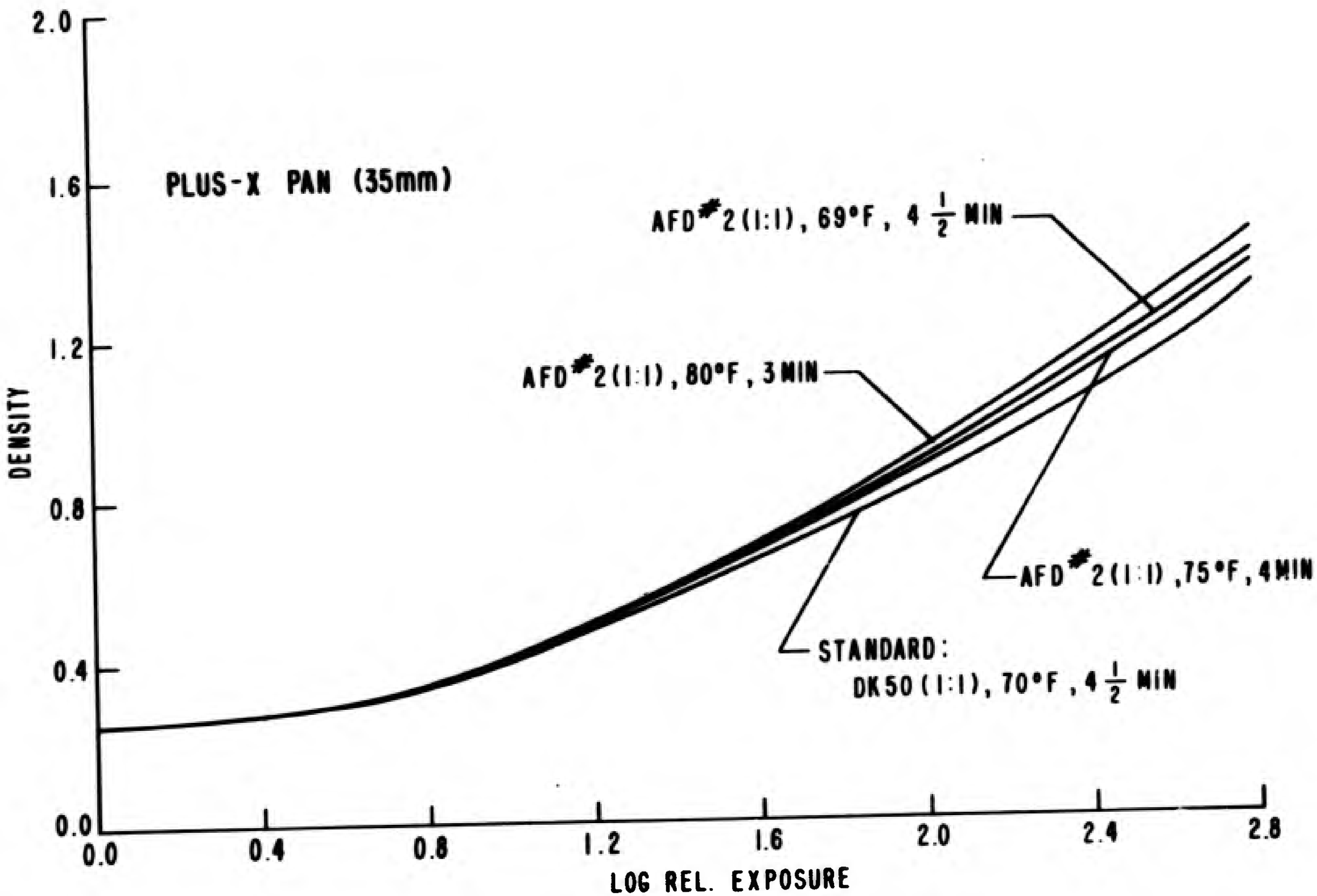
TIME / TEMP DETERMINATION FOR MANUAL PROCESS

FIG. 5



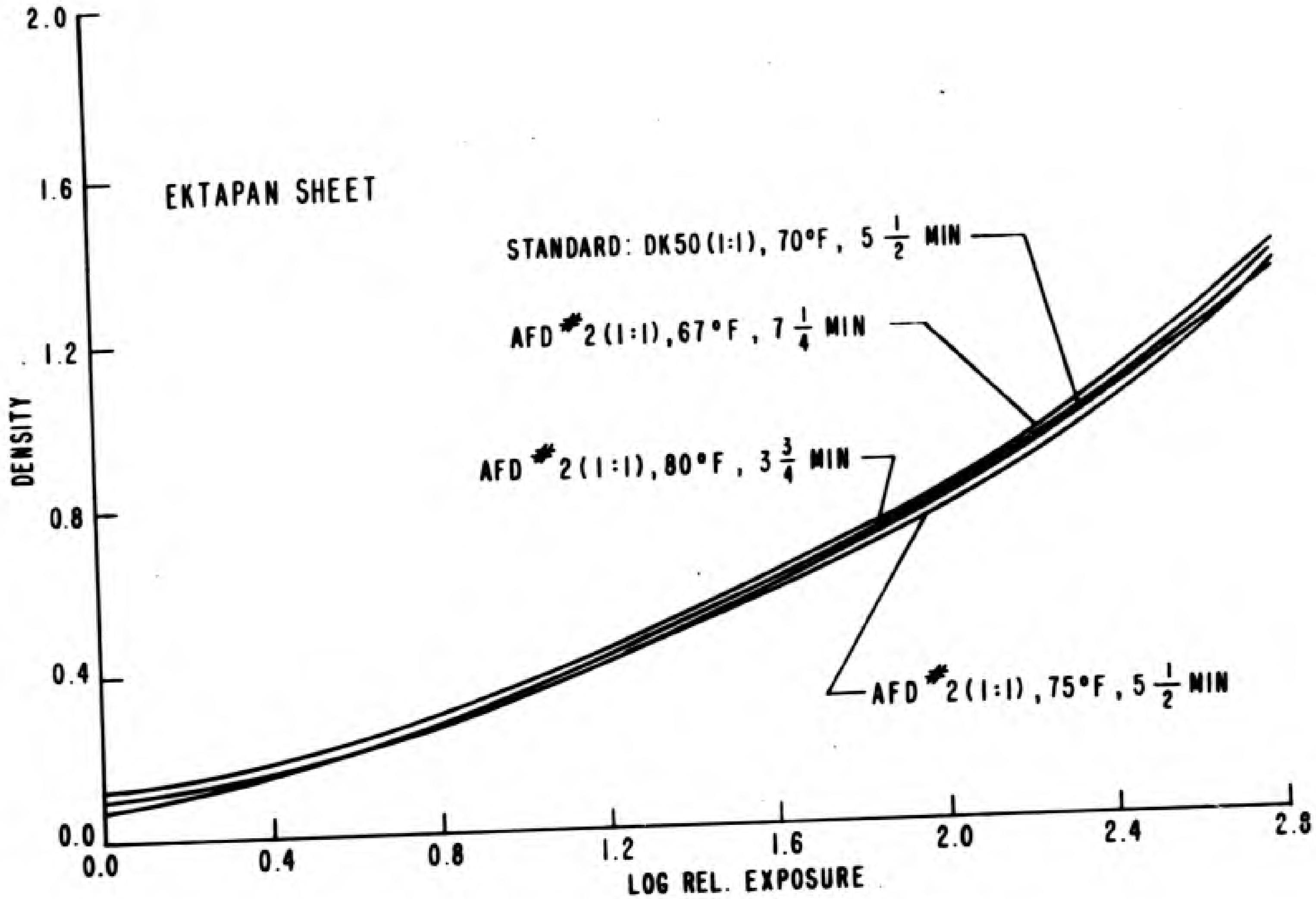
TIME / TEMP DETERMINATION FOR MANUAL PROCESS

FIG. 6



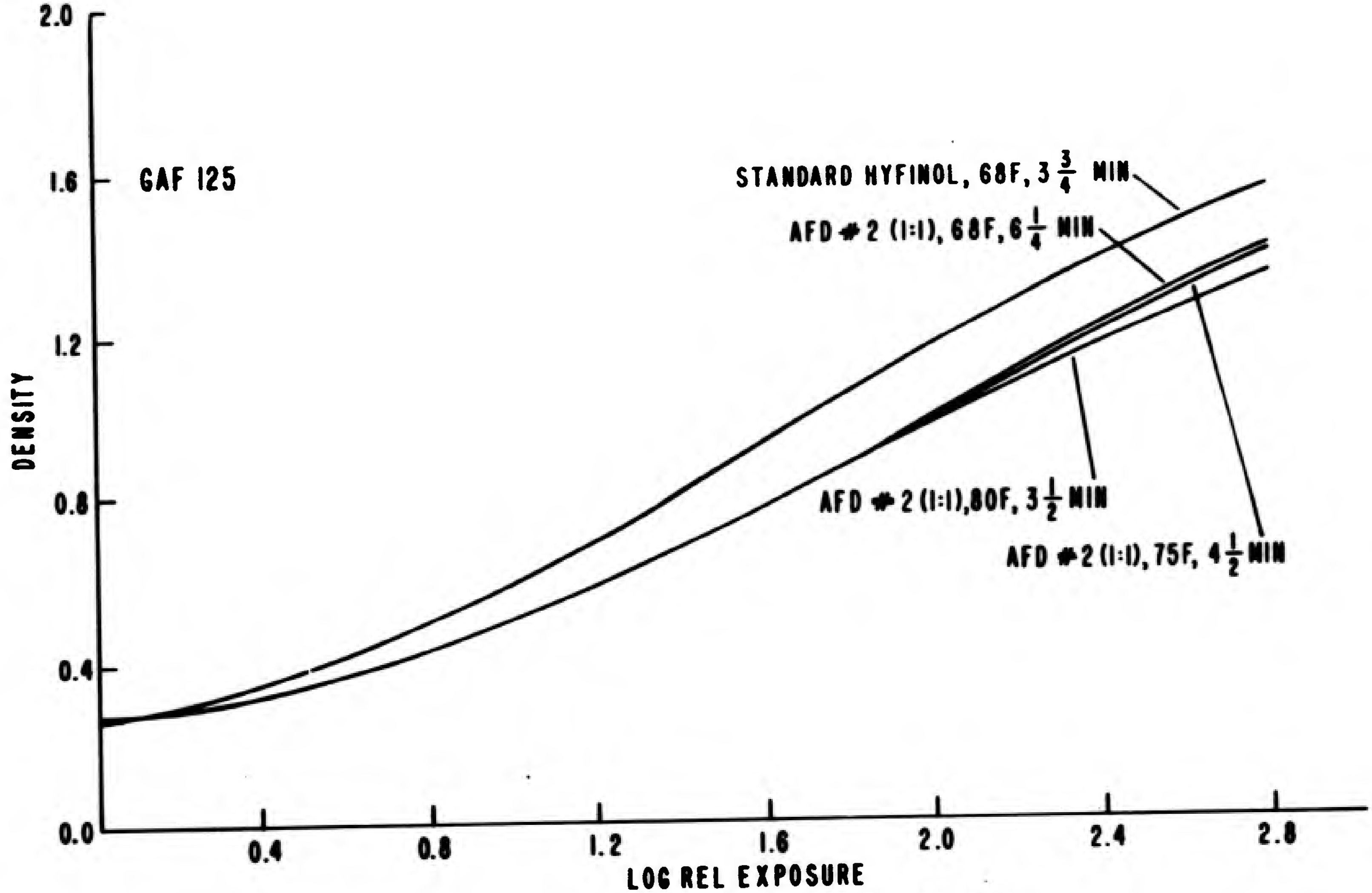
TIME/TEMP DETERMINATION FOR MANUAL PROCESS

FIG. 7



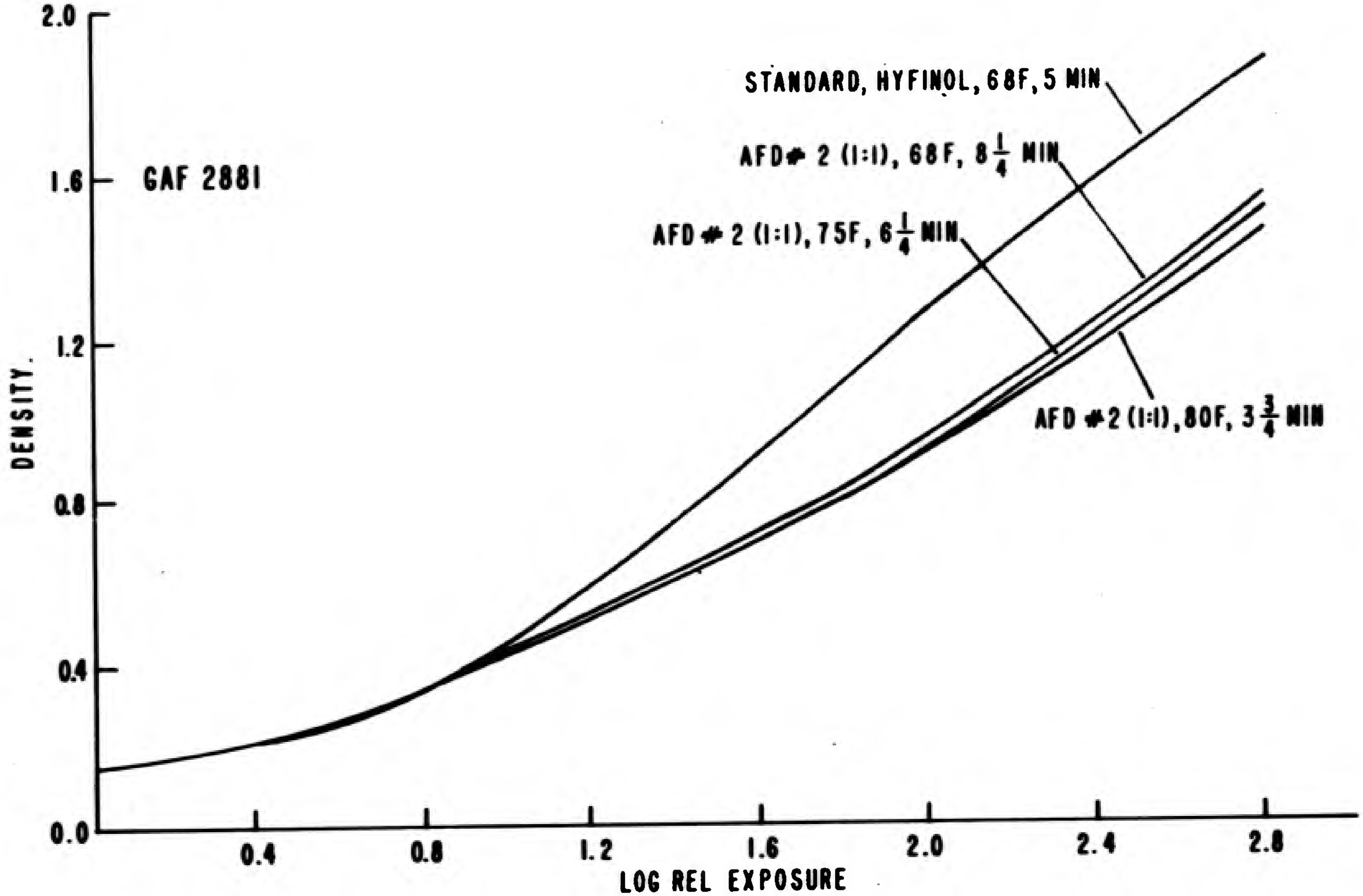
TIME/TEMP DETERMINATION FOR MANUAL PROCESS

FIG. 8



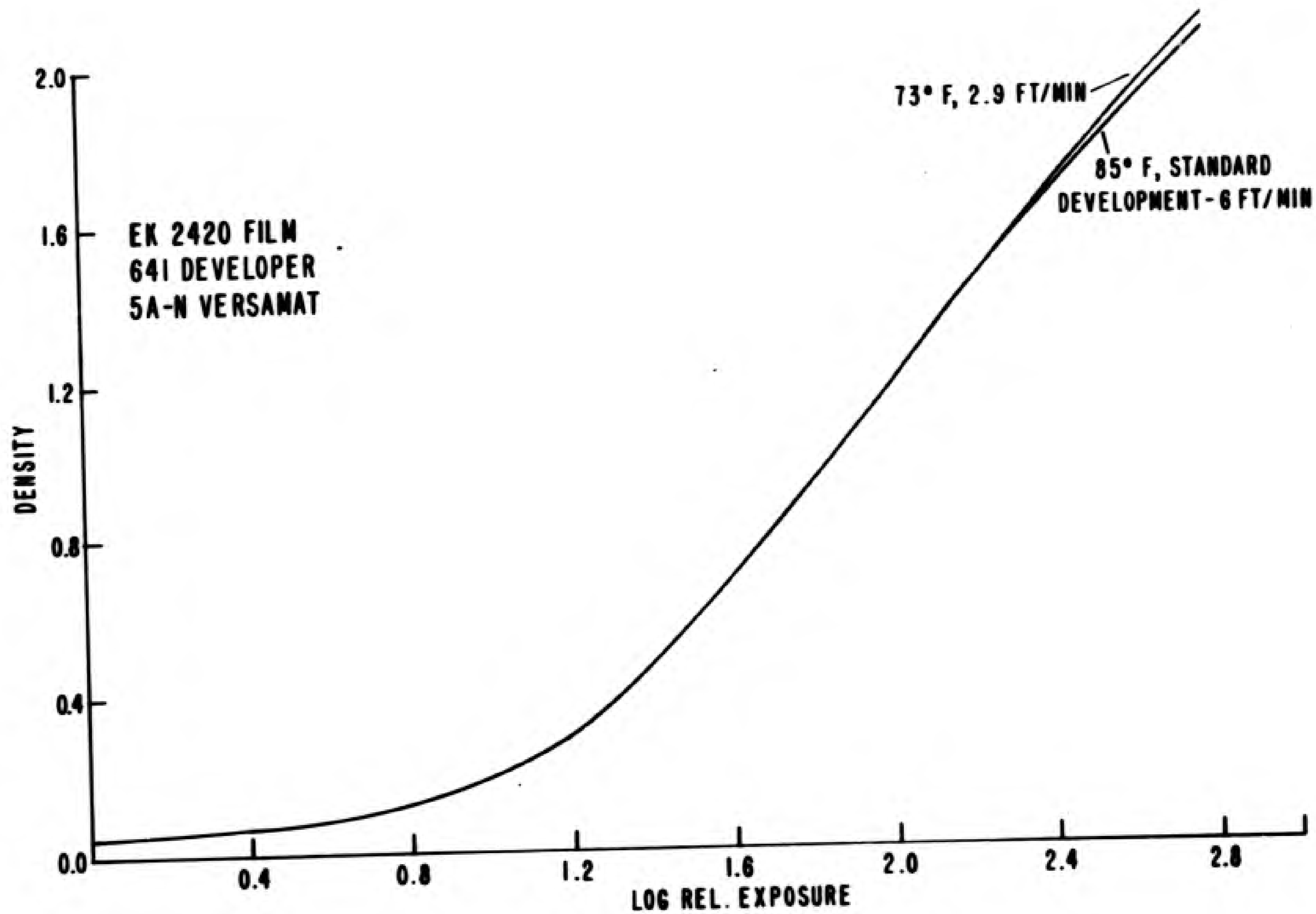
TIME / TEMP DETERMINATION FOR MANUAL PROCESS

FIG. 9



TIME/TEMP DETERMINATION FOR MANUAL PROCESS

FIG. 10



MACHINE PROCESSING USING SENSITOMETRIC CONTROL

FIG. 11

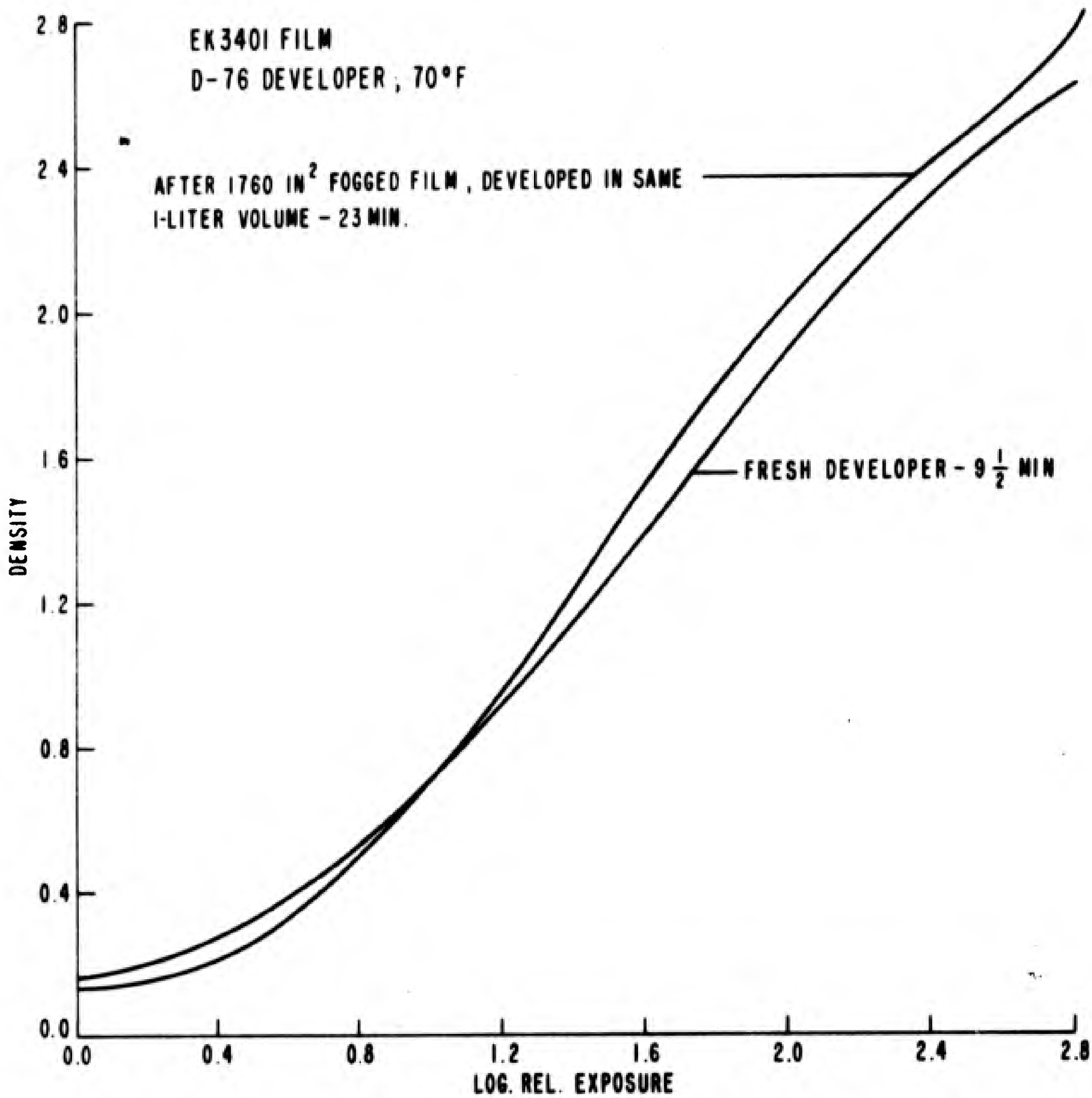
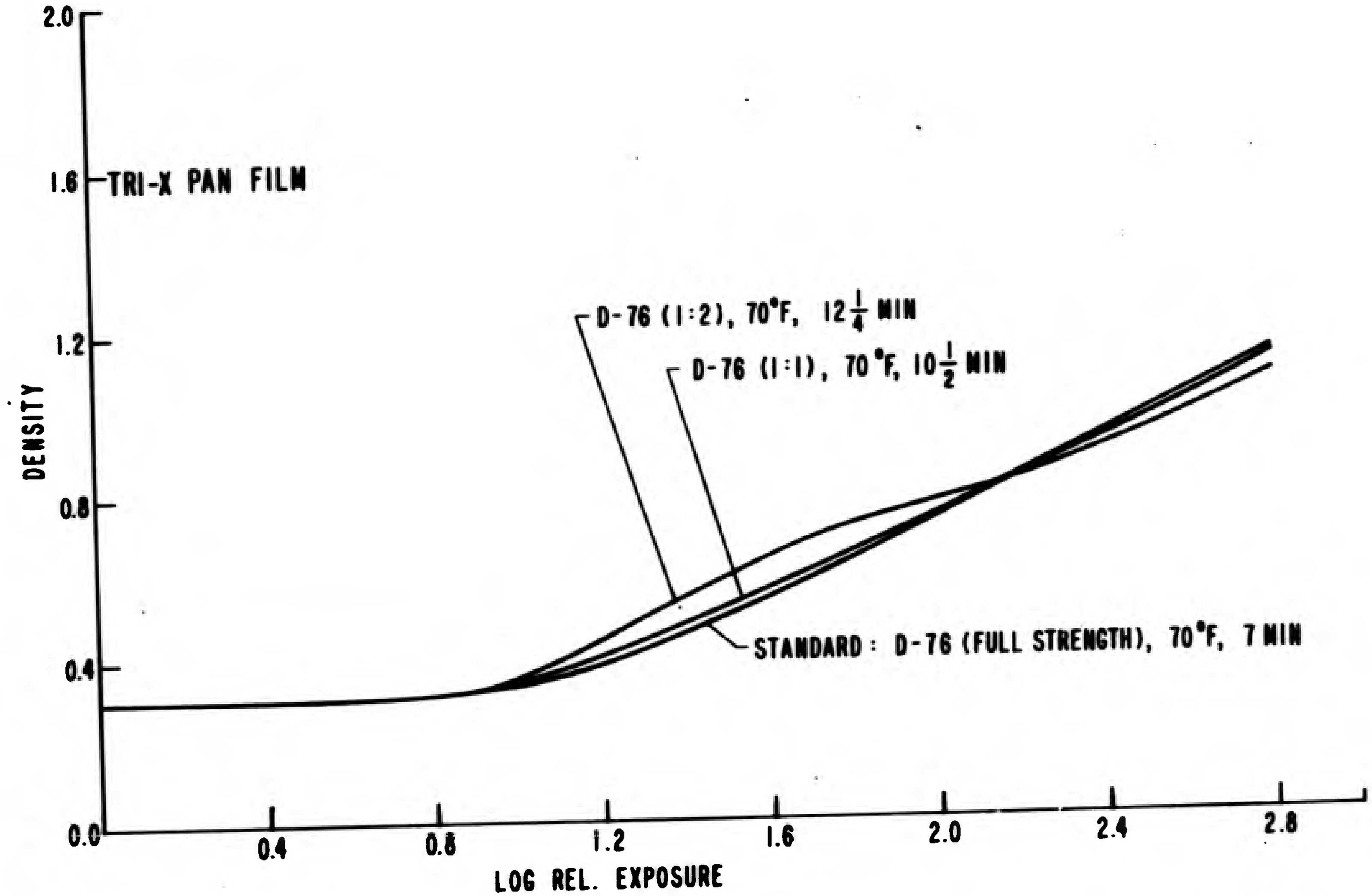
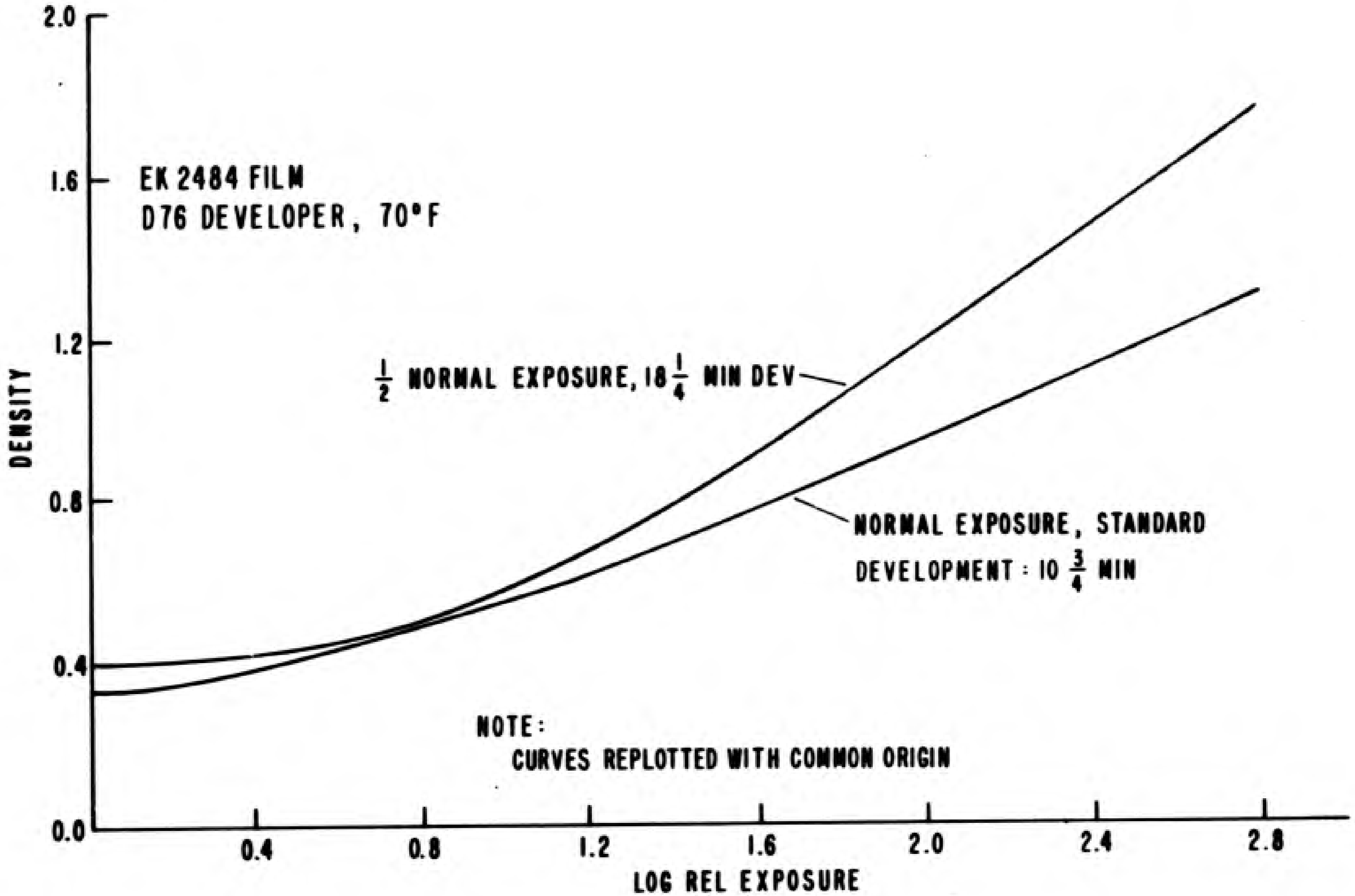

EK3401 FILM
D-76 DEVELOPER, 70°F
AFTER 1760 IN² FOGGED FILM, DEVELOPED IN SAME
I-LITER VOLUME - 23 MIN.
FRESH DEVELOPER - 9 1/2 MIN
DENSITY
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0
0.0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
LOG. REL. EXPOSURE

FIG. 12



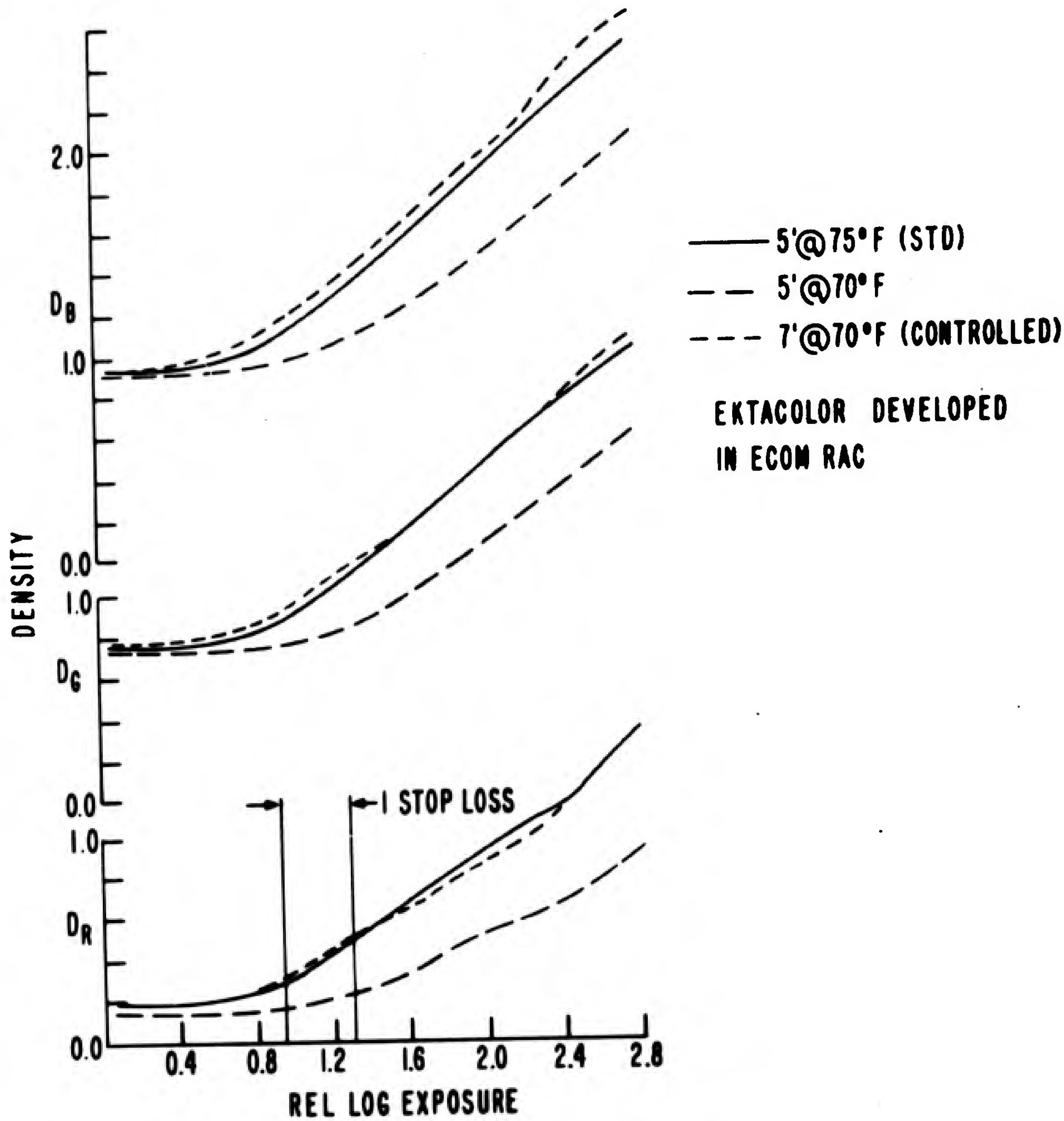
DEVELOPER DILUTION TEST

FIG. 13



UNDER EXPOSURE COMPENSATION

FIG. 14



COLOR PROCESS CONTROL

FIG. 15