SPACE ASTRONOMY

OF THE

STEWARD OBSERVATORY

THE UNIVERSITY OF ARIZONA
TUCSON, ARIZONA

TEMPERATURE EFFECTS ON PHOTOGRAPHIC SENSITIVITY

Supported Under NASA Grant NGR 03-002-032

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Author:

Dennis R. Hollars

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FOREWARD

The following Technical Report has been prepared from the final research paper submitted by Dennis Hollars in partial satisfaction of requirements of the Masters Degree at the University of Arizona. The work reported has been carried out under the direction of W. G. Tifft within the scope of the NASA NGR 03-002-032 Grant.

W. G. Tifft, Principal Investigator

ABSTRACT

The effect of temperature on the photographic sensitivity of three emulsions has been investigated over the restricted platen temperature range of approximately 16°C to -55°C. Exposures on Tri-X and Plus-X were made in neutral, red (6050Å), and blue (4490Å) light. The exposures on 103a-O were made only in neutral and blue light due to the insensitivity of 103a-O to light redder than about 5500Å. In each exposure a 12-step neutral density wedge was imaged on the film.

The results are straightforward. Each emulsion displayed a sensitivity dependence with temperature in each color. The Tri-X and Plus-X showed points of optimum temperature (at maximum density) within the range employed. The optimum temperature however was not constant but varied with emulsion, color, and light level. The optimum temperature in general increased with increasing light level and was apparently higher at all light levels for the red exposures than for the blue. The 103a-O displayed a nearly linear decrease in sensitivity with decreasing temperature. The point of optimum temperature for the 103a-O is therefore higher than 16°C at these light levels.

A comparison of the blue exposures of 103a-O and Tri-X reveals greater response for the Tri-X at the fainter light levels. However,

the effect is reversed in the higher light levels. This response is interpreted as a difference in gamma of the two emulsions. The fact that the optimumly cooled Tri-X is more sensitive to blue light than the 103a-0 at the lower light levels is not important to astronomical photography unless the same effect occured at much longer exposure times and fainter light levels.

I. INTRODUCTION

Observational astronomy has long depended upon the photographic plate as a reliable means of gathering and storing large amounts of data. Today photoelectric techniques have replaced the photographic plate in areas where greater accuracy is necessary, but the photographic plate retains its usability where the advantage of rapidly recording large amounts of data outweigh the loss in accuracy. Hoag (1961) has shown that some emulsions display gains in speed of one or two stellar magnitudes when cooled to -35°C (platen temperature). He has pointed out the possible uses of fine-grained cooled emulsions in spectroscopy and has used cooled color film to detect H_α emission regions. Hoag (ibid.) has shown that cooled color film retains its color balance in long exposures and could be used to provide a means of rapidly selecting color and magnitude sequences in clusters for later study by photoelectric methods. Further study in this area could indeed lead to very fruitful results.

The initial intent of this investigation was to provide a quantitative comparison of three emulsions at faint (astronomical) light levels as a function of temperature and wavelength. It was anticipated that the investigation would provide an answer to this question.

Will optimumly cooled Tri-X perform as well as the uncooled but chemically adjusted 103a-O? Unfortunately the amount of time available to the investigator was very limited due to circumstances beyond his control; additionally, some equipment problems arose the sum of which necessitated a compromise in the extent of the investigation. As a result the study was limited to a relative comparison of the sensitivity of three emulsions as a function of wavelength and temperature at a rather high light level.

Although the study does not provide any unexpected results, it is hoped that it does qualify in method as a way to obtain basic comparative data about photographic response. It is realized that a fully complete investigation of just a single emulsion must go far beyond the comparative methods used here.

This investigation was the first project attempted using a faint signal detection system developed under the direction of Dr. W. G. Tifft. It provided a shake down of some of the systems and revealed some problem areas that have since been remedied. The completed system now provides a far wider range of experimental conditions than those that were available when the data for this investigation was obtained during the summer of 1966. I wish to thank Dr. Tifft and his staff for their untiring efforts in solving problems fast enough to allow this data to be obtained in the short period of time that was available. A special acknowledgement is made to Dr. Tifft for his aid in interpreting the results and patience in seeing the project to completion.

II. EQUIPMENT & DATA COLLECTION

A schematic of the signal detection system layout is shown in Figure 1. A Baush and Lomb tungsten lamp was used in conjunction with two Balzers filters and a neutral filter to provide red, blue and neutral colors. The neutral color was essentially that provided by a blackbody at the lamp temperature of about 3000°K. The Balzers filters provided radiation near 4490Å (blue) and 6050Å (called red) with a half-width of about 110Å.* A blackbody at 3000°K would have a radiation peak near 10,000Å. When the transmission curves for the two Balzers filters are convolved with the blackbody curve, the peaks in transmission would be shifted to the red by a small amount, but since this is a comparative study the absolute values of the transmission peaks are more or less academic. The opal glass was used to make the illumination on the wedge as uniform as possible. Neutral density filters were added as needed to bring the light level to the proper value.

The photographic wedge consisted of twelve neutral density steps arranged in two rows of six. It was scanned several times with the microdensitometer with very consistant results. The step wedge calibration is shown in Table 1. Listed from left to right are the step number, the measured % transmission of each step, the relative I·t values (scaled from the transmission), and the $\log(I \cdot t)_{rel}$ values. Each H & D plot uses the $\log(I \cdot t)_{rel}$ values as the abscissa but the scale is not shown since it is the same for every curve.

* Plots of % transmission vs. λ are provided for each filter in Appendix A. The scans were made with the spectraphotometer at Kitt Peak National Observatory.

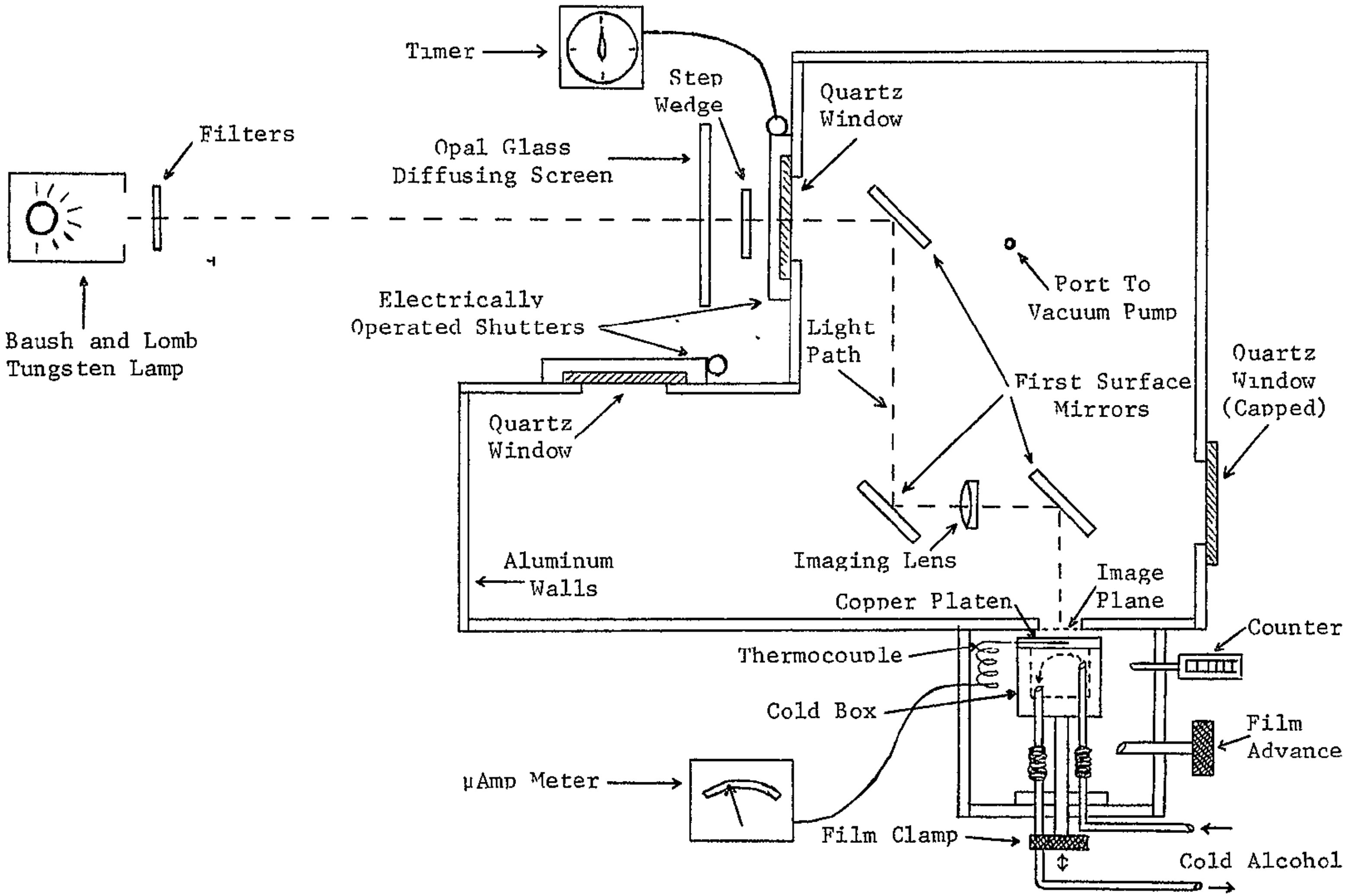


Fig. 1. -- Top view of signal detection system layout.

Step Number	% Trans.	$(I \cdot t)_{rel}$	$Log(I \cdot t)_{rel}$
1	.24	.262	-.582
2	.46	.503	-.298
3	.80	.875	-.058
4	1.30	1.42	.152
5	2.0	2.19	.340
6	3.0	3.28	.516
7	9.0	9.85	.993
8	14.0	15.3	1.177
9	23.0	25.2	1.398
10	37.0	40.5	1.603
11	63.5	69.5	1.842
12	91.5	100.0	2.000

Table 1. Step Wedge Calibration

Light was admitted to the vacuum chamber through an electrically operated shutter which was connected so that it would remain open as long as a darkroom timer was running. The timer was set for an exposure, and when it was started, the shutter would open. When the time expired, power was automatically denied to the shutter causing it to close. Thus, although the absolute length of an exposure was not known with precision, it was consistantly repeatable.

Inside the vacuum chamber the light was reflected by first surface mirrors to an achromatic lens spaced such as to produce an image of the wedge at the image plane. A movable platen held the film against the image plane during exposure while a flow of cold alcohol maintained the lower temperatures. An Iron-Constantan thermocouple embedded in the platen was used to secure temperature measurements. A calibration was run with the thermocouple and meter bracketing the temperature range employed in the study. The points scattered very closely around the standard Iron-Constantan curve given in the Handbook of Chemistry and Physics; therefore, the standard curve was used to reduce the meter readings to platen temperature.

Five significant problems were encountered during the first attempt to obtain data. They were (1) film breakage during advancement, (2) static exposures on the Tri-X and Plus-X, (3) several vacuum leaks, (4) pump failure at the lower temperatures, and (5) failure of the mixing valves to supply warm and cold alcohol from their respective baths at constant rates.

The film breakage was attributed to the vacuum binding of the rubbing metal surfaces in the metal sprockets and film pullies. A light coating of vacuum grease on each surface solved part of the problem. It was finally eliminated by not ridgedly attaching the film to the supply spool in the cassette. Thus the film would come out of the cassette freely without turning the spool.

The arcing was more difficult to handle. Even though the entire system was grounded to water pipes, static spark exposure would occur on the Tri-X and Plus-X regardless of how slowly the film was advanced. Various tests isolated the major trouble spot to be at the copper platen. The 103a-0 refused to show any arcing regardless of how it was treated.

It was assumed that the wavelength region of the spark was either outside the sensitive range of the 103a-0 or the backing on the 103a-0 was conductive and arcing was prevented. After assuming the latter to be correct, a can of anti-static record spray was procured. The Tri-X and Plus-X were unrolled in total darkness and placed emulsion side down on a clean dry surface and a very light coat of spray was applied to the backing. The film was then rewound into cassettes. Tests showed that no arcing was noticeable when the film was advanced slowly. The effect of the spray on the photographic properties of the film is not known.

Vacuum problems are immense when a large volume is to be sealed. Initially the vacuum box was bolted together with the edges sealed with vacuum wax and glyptal, but a sufficiently low vacuum to prevent water condensation on the emulsion could not be attained. A major leak was discovered around the lead to the thermocouple which large amounts of wax and glyptal finally reduced. Many small leaks sprang up around the joined edges of the camera, but were finally sealed by many coats of glyptal. Eventually a pressure of 1000μ could be obtained with a few minutes pumping. Sometimes the pressure would go as low as 500μ but it seemed temperature dependent. At these pressures no condensation marks were readily noticeable on the film, so it was deemed adequate. Two principles of vacuum technique appear to come out of this experience. First, weld every joint that is considered permanent, and secondly design every port as on O-ring seal in unjoined metal.

The problem with the pump was initially assumed to be one of conventional bearing grease freezing at the lower temperatures and halting the pump. After the pump was replaced with one featuring dry graphite lubrication, temporary success was enjoyed. At the end of the final run this pump also stopped. Although the exact cause is not known, it was probably the result of moisture condensing on the bearing surfaces and freezing.

Figure 2 shows the physical layout of the temperature controlling system. Sources of warm and cold methyl alcohol were provided as inputs to the pump. Dry ice in methyl alcohol was used to give a constant low

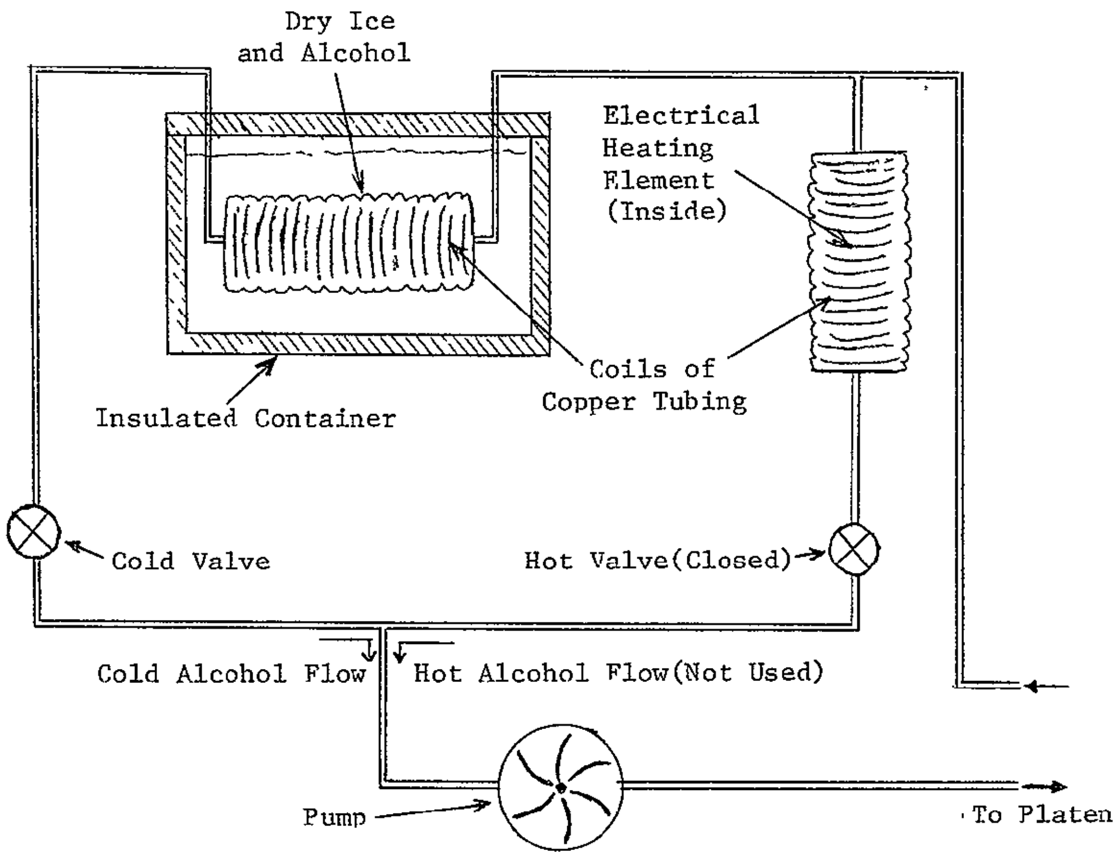


Fig. 2. -- Schematic of the physical layout of the temperature controlling system.

temperature cold bath. A ceramic heating element was used to warm returning alcohol by conduction through the copper lines. By properly positioning the valve on each bath it was anticipated that a given ratio of warm and cold mixed alcohol could be achieved at the platen to give constant intermediate temperatures. It was soon discovered that only two constant temperatures could be obtained -- one warm and one cold. However one could watch the thermocouple output meter and keep any intermediate temperature by alternately starting and stopping the pump with only the cold valve open. This was the method used during the exposures, and it therefore introduces an amount of uncertainty into the platen temperature; although, with a little practice the needle on the meter could be held rather constant. These two problems -- pump freezing and difficulty in holding a constant temperature -- were the principle factors which limited the study to one at short exposure times and higher light levels, since time was not available to see the problems to a better solution.

A typical run proceeded in the following manner. The film was coated with the anti-static record spray as needed and then loaded into the camera. The vacuum pump was started and allowed to run for thirty minutes; the resulting pressure being about 500μ. First the neutral filter then the red and blue were used for exposures at ambient temperature. Then the pump was turned on for a short burst to give a temperature drop of about 8 to 10 degrees. No effort was made to repeat exact temperature settings; the meter readings were simply recorded. The film was advanced and the temperature was held nearly constant by short bursts of pumping. At least two minutes were allowed to let the film come to equilibrium with the platen -- the actual film temperatures were probably several degrees warmer then the platen. The first exposure at each cooler temperature was made with the same filter arrangement as the last exposure at the higher temperature. Then the other filters were used in turn to complete the exposures at that temperature setting. The temperature was again lowered a few degrees and the procedure was repeated. As lower temperatures were reached more coolant pumping was required to maintain them. At the lowest temperature of about -55°C continous pumping was required. At the lower temperatures the vacuum went up to 1000μ, but no condensation marks were visible on the emulsion.

Each blue exposure was of 15 seconds duration at constant light level. Similarly the red exposures were each 5 seconds duration at constant light level. The exposures in neutral light were all of 30 seconds duration. The light level was the same for 103a-0 and Plus-X, but a 20% transmission neutral density filter was added for the Tri-X due to its faster speed. The ratios of the various light levels are known therefore permitting relative comparisons to be made.

Development was accomplished as soon as each run was completed. The 103a-0 was developed in D-19 under conditions recommended by the manufacturer. The Tri-X and Plus-X were developed in Acufine also under recommended conditions. The pertinent data on the film parameters and exposure conditions are given in Appendix B.

III. DATA MEASUREMENT

The Hilger-Watts microdensitometer at the Steward Observatory was utilized for measuring the transmission in each step of the seventy-four wedge images. Before any measurements were taken the microdensitometer and the strip chart recorder were turned on and allowed to warm up for several hours. The two glass plates between which the film was placed during a measurement were cleaned and positioned in the light beam during all calibrations. Therefore the 100% level of transmission was scaled to allow for the attenuation in the glass plates. The zero level was achieved by completely attenuating the light through the slit with an opaque object. Each wedge scan was made with constant slit setting and identical orientation of the wedge image.

A typical example of the strip chart recorder output is shown in Figures 3 and 4. Figure 3 is the result of scanning the first six steps (fainter images) on one side of the wedge. The direction of the scan proceeded from the least dense step toward denser steps. Figure 4 shows the output of the scan of the six denser steps. On this scan the machine sensitivity was changed from X1 to X5. Many times during the measurements steps 7 and 8 were measured at both sensitivity settings to serve as a check on the instrumental scale factor of 5. From the measurements of steps 7 and 8 at both settings, an average sensitivity factor of 5.02 was found with a scatter of about 1%. Therefore in the data reduction 5.00 was used.

In the microdensitometer tracing in Figures 3 and 4 the straight line represents the average per cent transmission of the fog level of the film. The positions marked step #1 to step #6 or step #7 to step #12 represent the points chosen for the measurement of the % transmission of the fog level and the corresponding % transmission of the step. In some cases this tolerance for the measurement of the % transmission of the step had to be relaxed due to severe fluxuations in the tracing caused principally from dust and other obscuring matter on or in the emulsion. It is obvious that steps 4 and 5 were measured far from step center. Steps 4 and 5 had a significant intensity gradient across them although no gradient was detectable in the scans of the wedge itself. Therefore, it was attributed to scattered or stray light in the system. Possibly it was a reflected ghost from the imaging lens. The measurements were made near the higher transmission points in these steps since the effect of stray light would be to lower the transmission. As far as the comparison between emulsions is concerned, it would not matter where in the step the density was measured as long as it was kept constant. However, the H & D curves might show odd shapes. One always

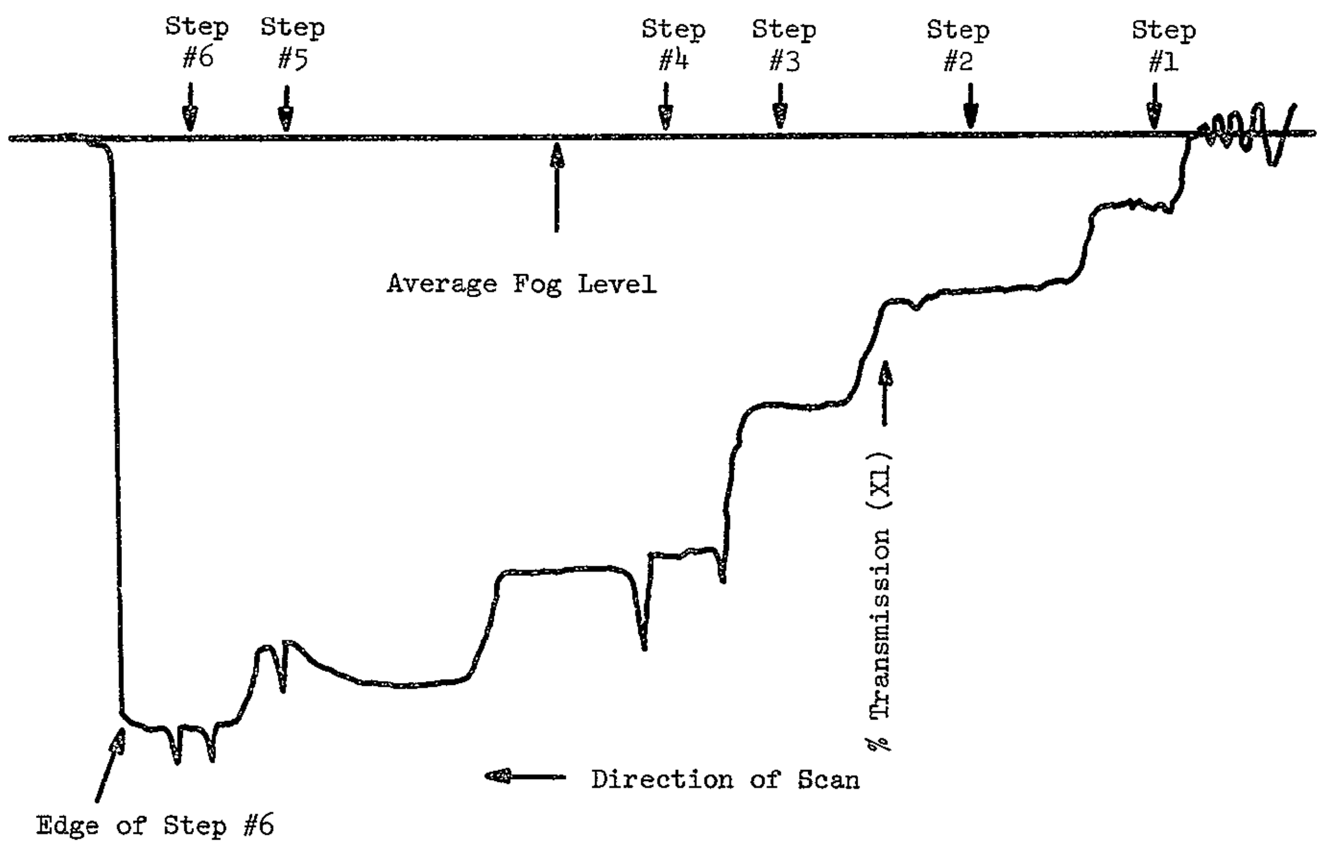


Fig. 3. -- Microdensitometer scan of Steps 1 through 6.

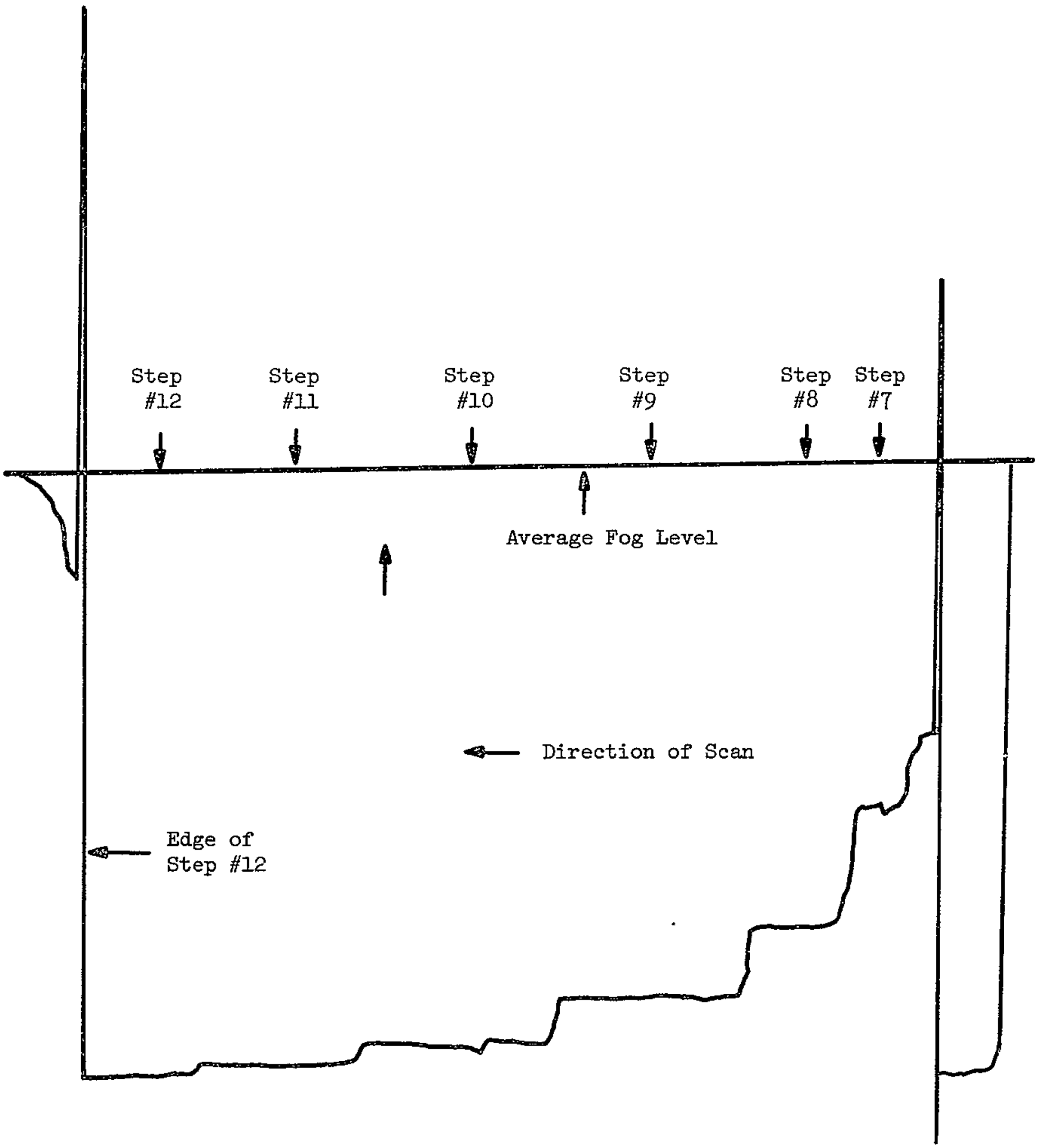


Fig. 4 -- Microdensitometer scan of steps 7 through 12.

hopes that in measurements made under these rather subjective conditions some semblance of regularity can be achieved. The fact that the completed H & D curves resemble standard H & D curves, lends some credence to the data and to the way in which the measurements were made.

Appendix C is a tabular list of the basic measurements made from the strip chart recordings. At the head of each section is listed the film type, the color, and the time of the exposure. Each block gives the exposure number and the platen temperature. The first column lists the step number from least dense to most dense. Column two is the per cent transmission of the fog level made at each numbered position as shown in Figures 3 and 4. The third column is the per cent transmission of the steps also measured at the numbered positions in Figures 3 and 4. The values for steps 7 through 12 have been divided by five so that each step has equal weight. The fourth column simply gives the transmission of the step with the fog level scaled to unity. The last column is the density of each step defined in the normal way, that is $D=-\log(1/T)$.

IV. DATA PRESENTATION

The data listed in Appendix C is presented in graphical form in Figures 5 through 12. Basically each dashed curve is an H & D plot for each exposure. The ordinate is the density and is plotted for each step of the wedge image. The abscissa for each curve in the graphs is a relative $\log(I \cdot t)$ scale, but it is not shown. For each graph I (the intensity) and t (the exposure time) were constants; therefore, $\log(I \cdot t)$ has the same relative value for the same step in each plot. A template was formed which had a convenient $\log(I \cdot t)$ scale. The abscissa became a linear temperature scale and each H & D curve was begun at the platen

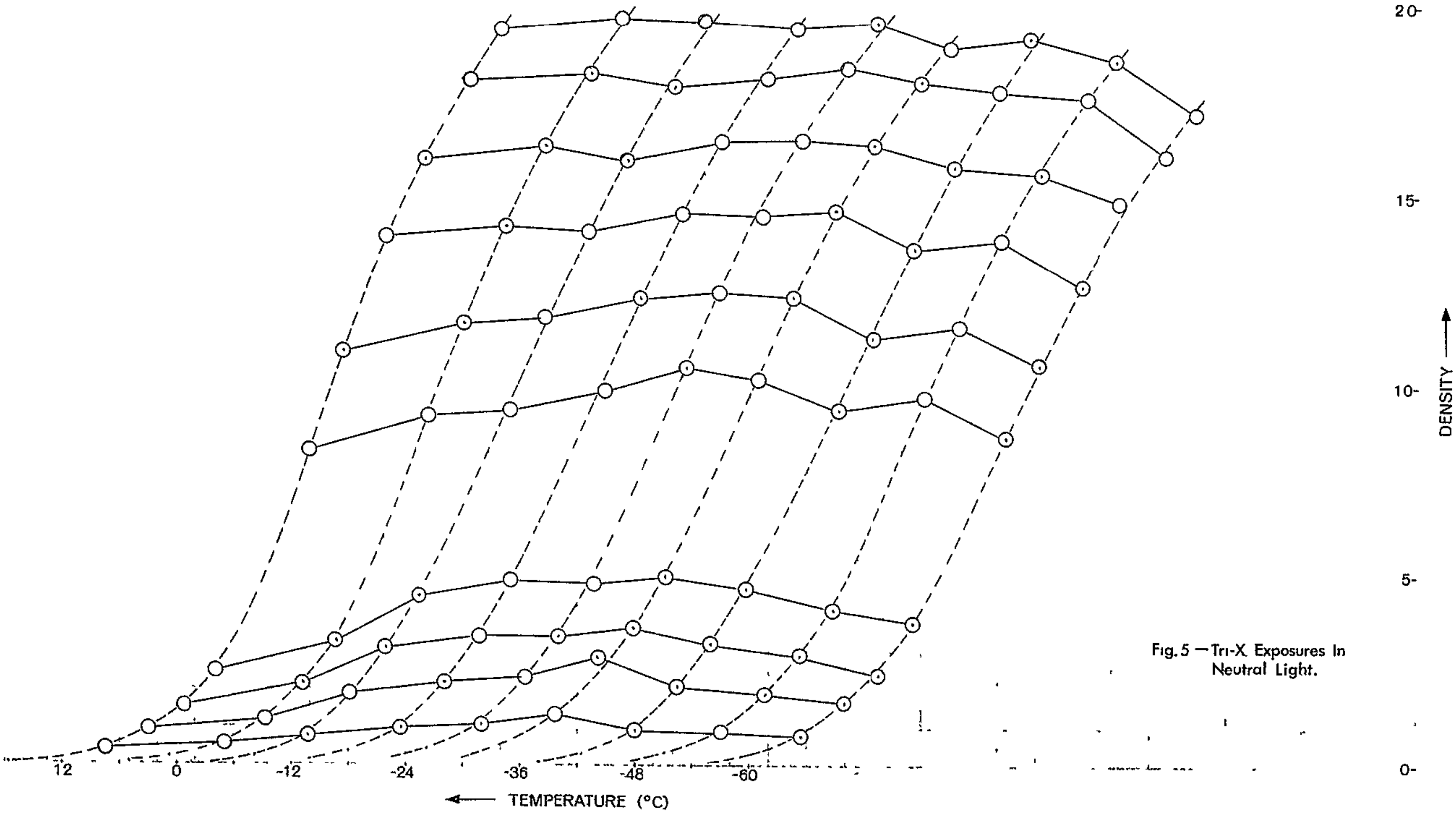


Fig. 5 — Tri-X Exposures In Neutral Light.

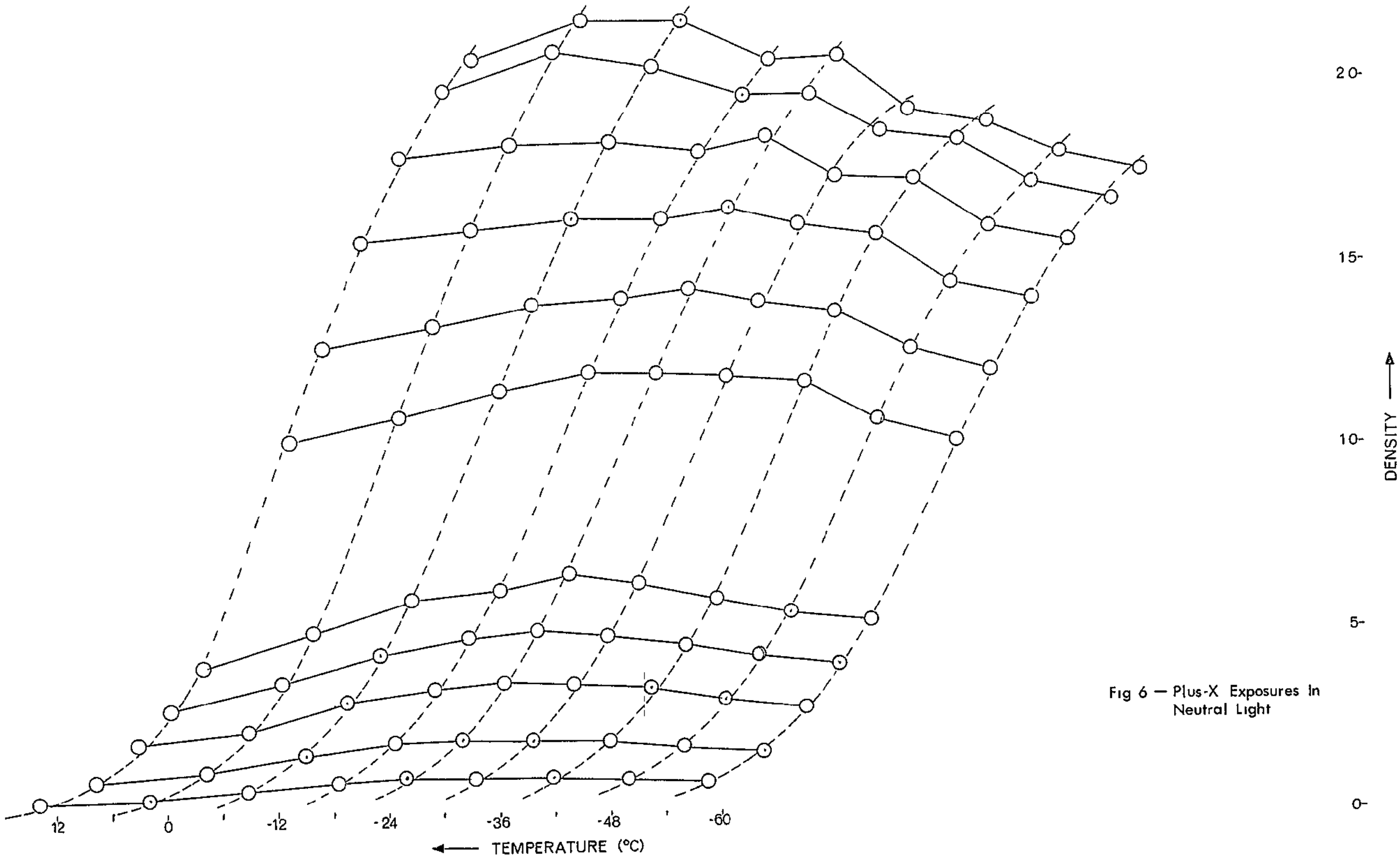


Fig 6 — Plus-X Exposures In Neutral Light

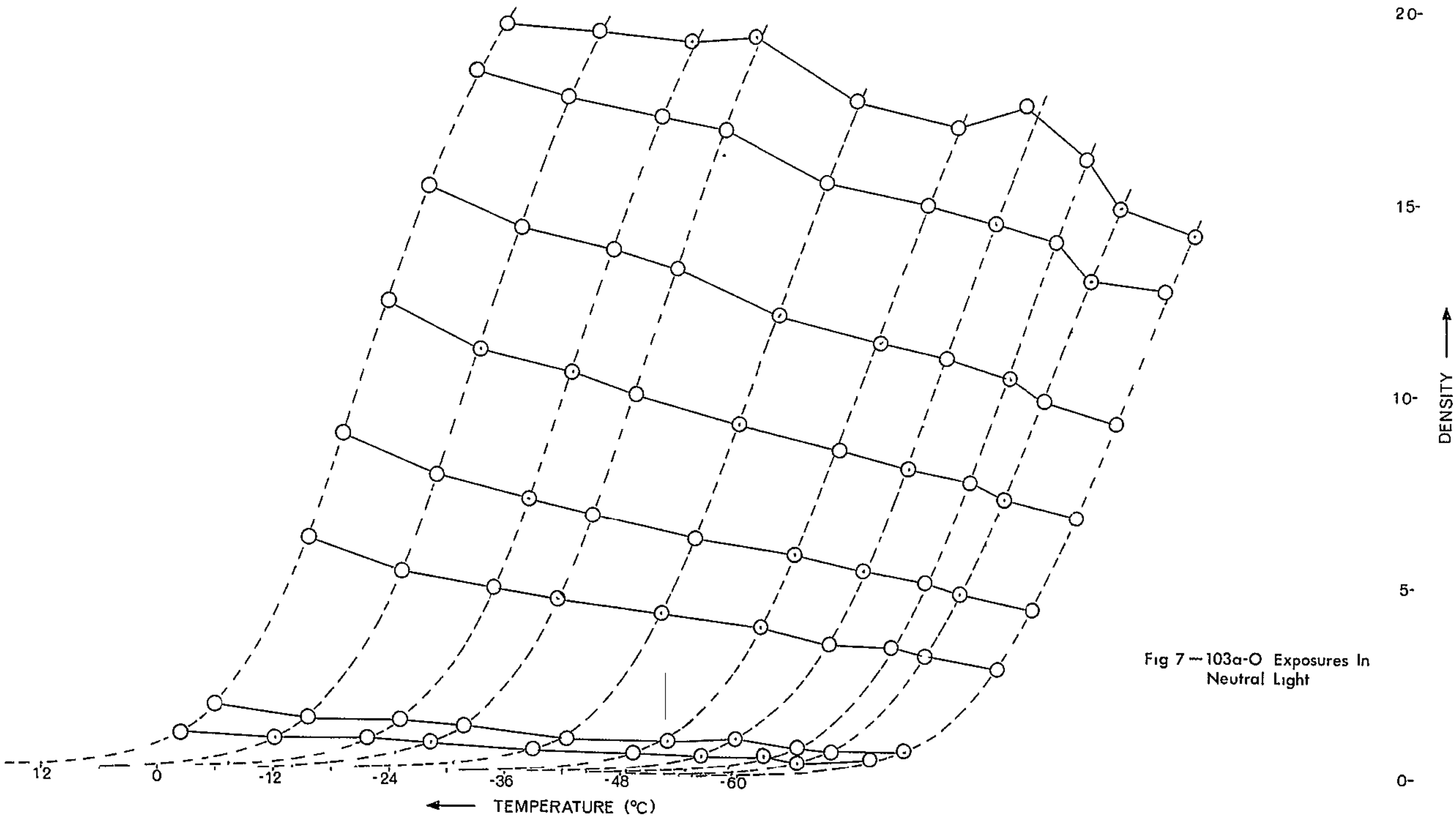


Fig 7 — 103a-O Exposures In Neutral Light

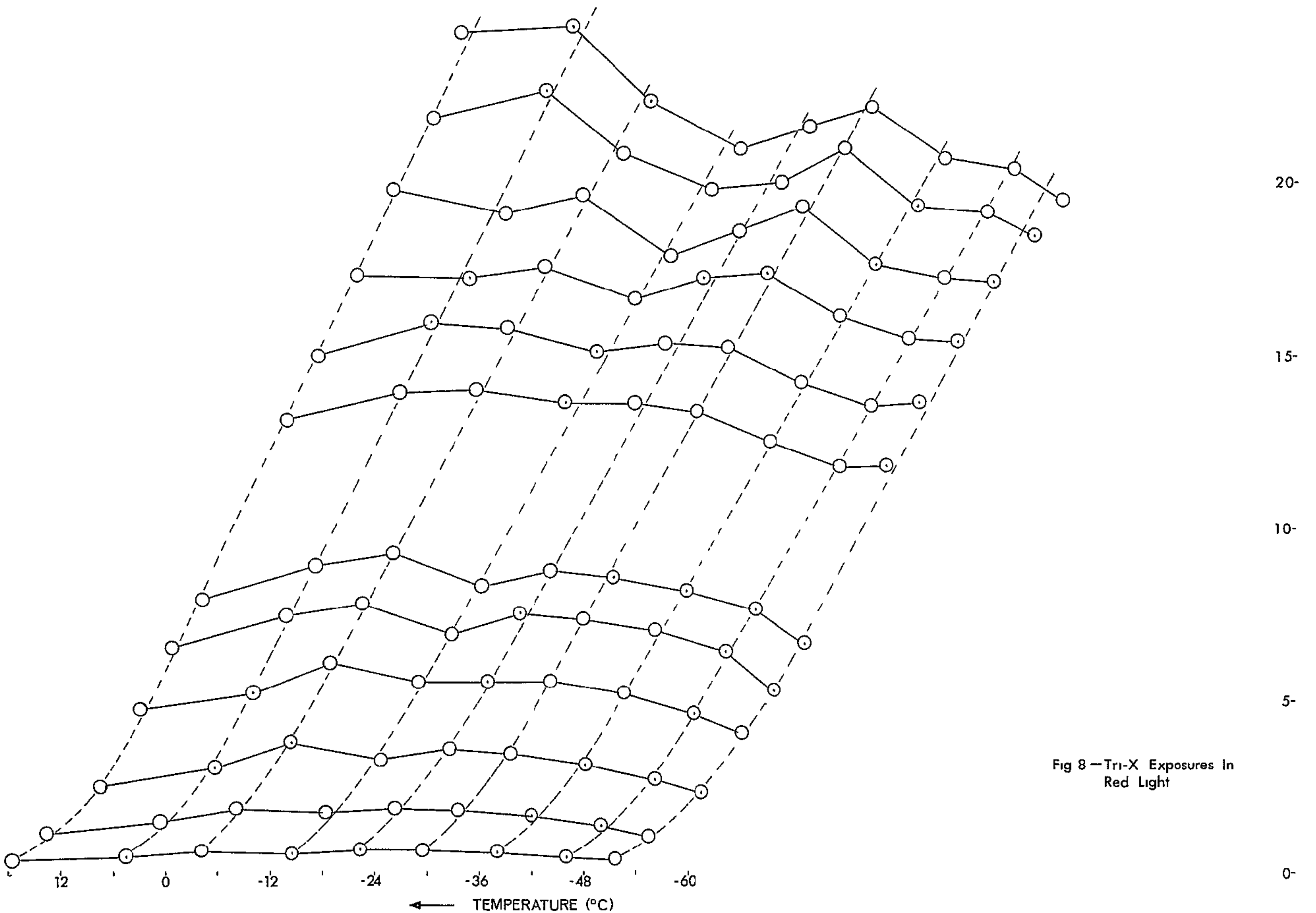


Fig 8 — Tri-X Exposures In Red Light

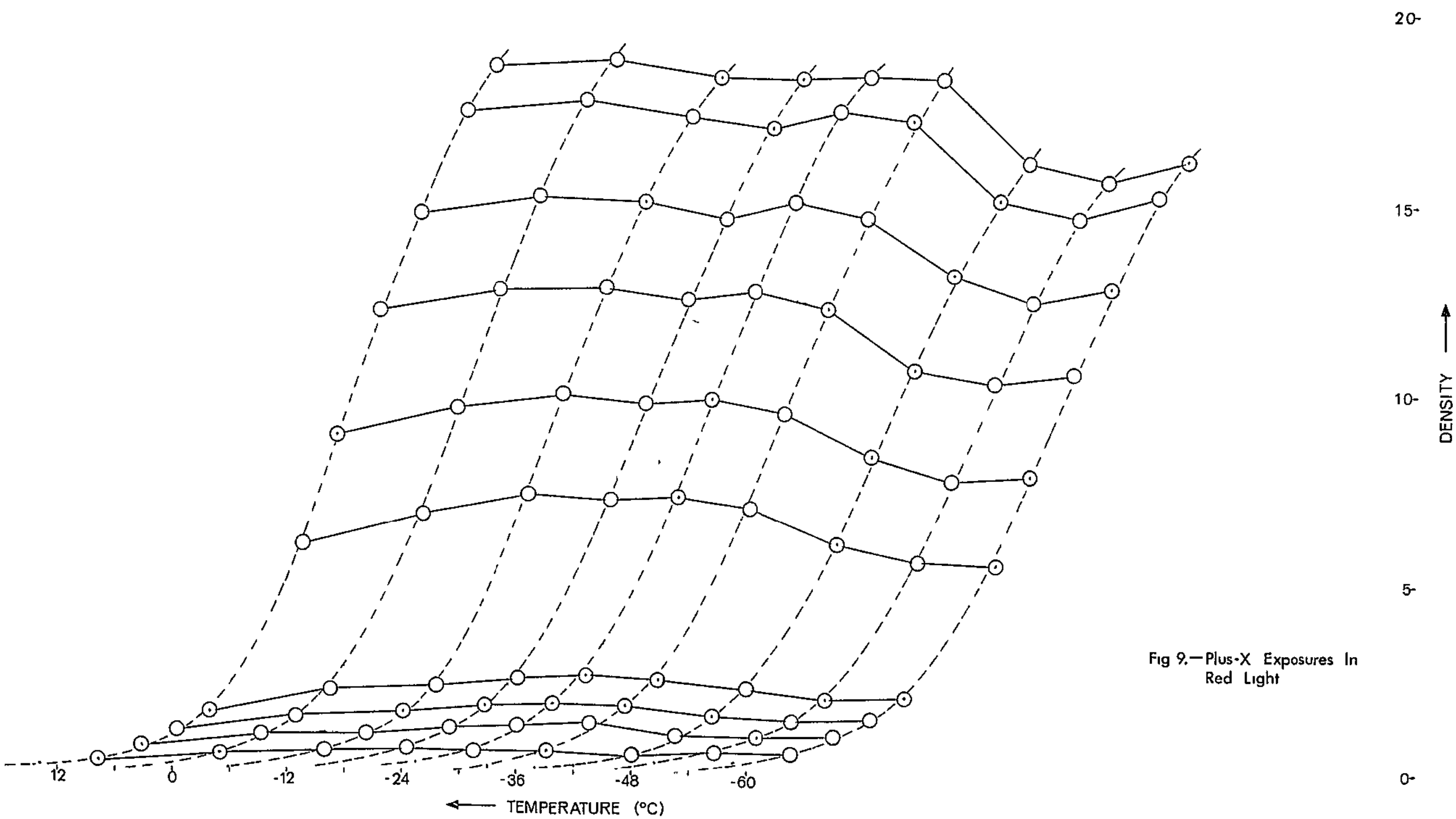


Fig 9.—Plus-X Exposures In Red Light

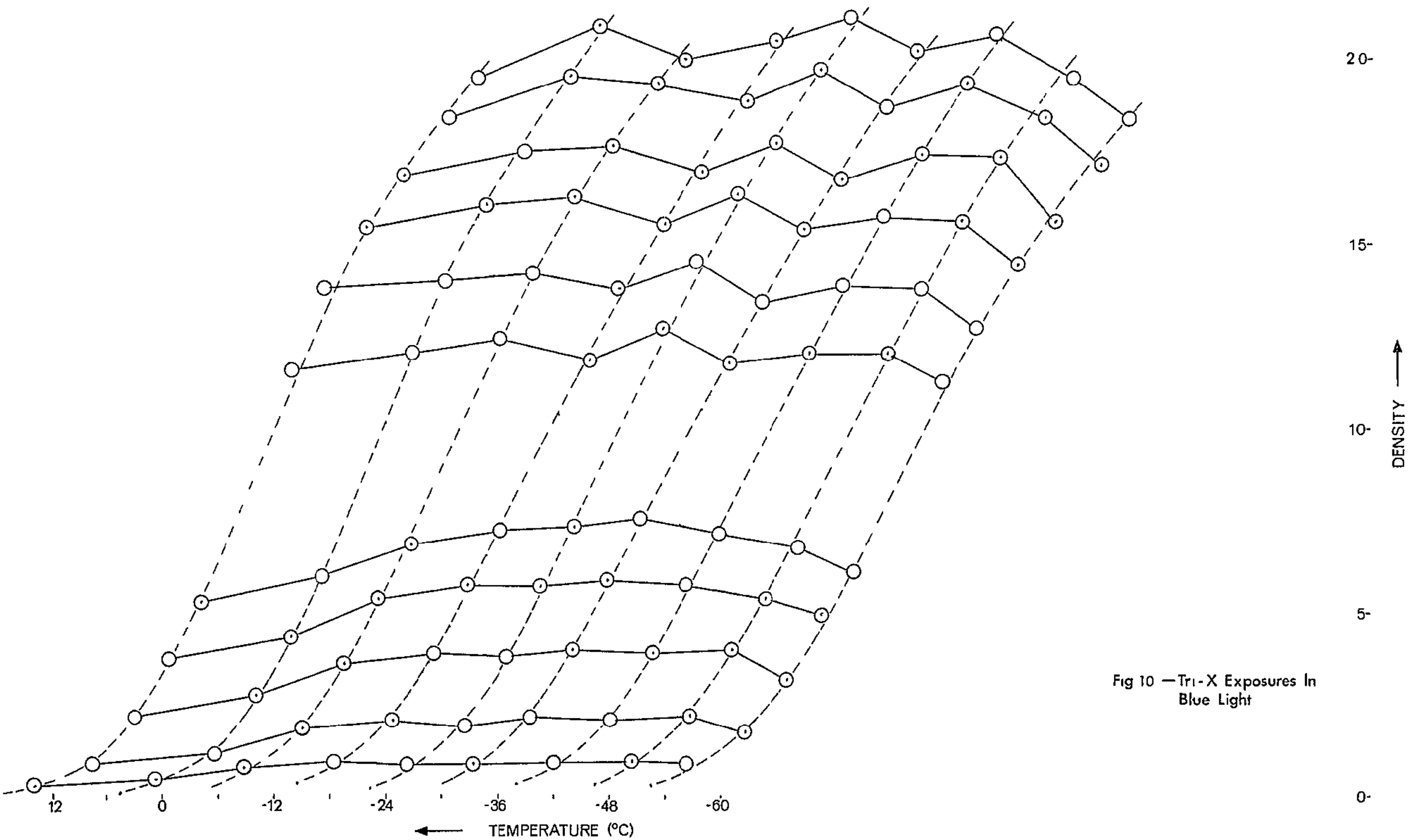


Fig 10 —Tri-X Exposures In Blue Light

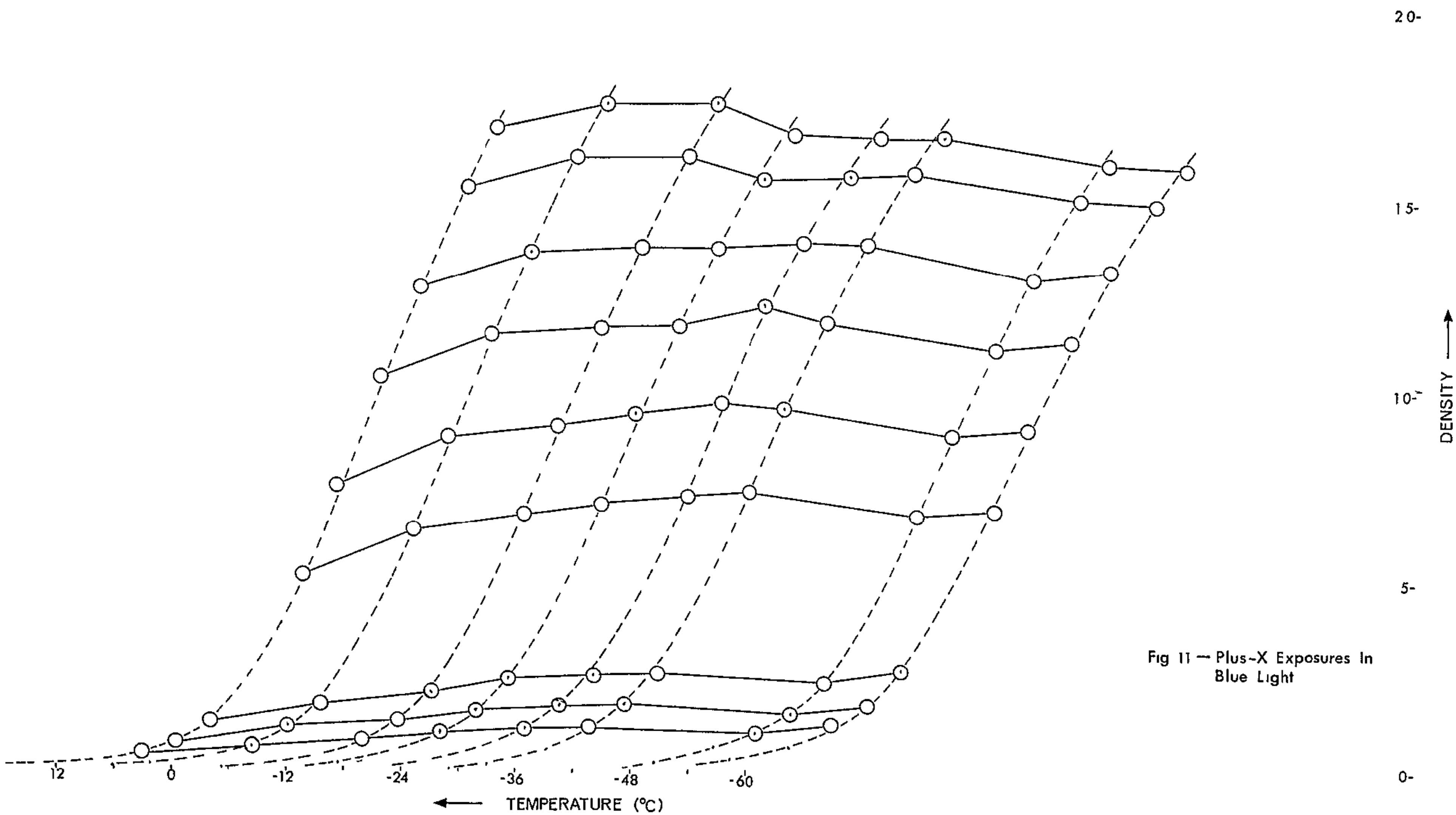


Fig 11 — Plus-X Exposures In Blue Light

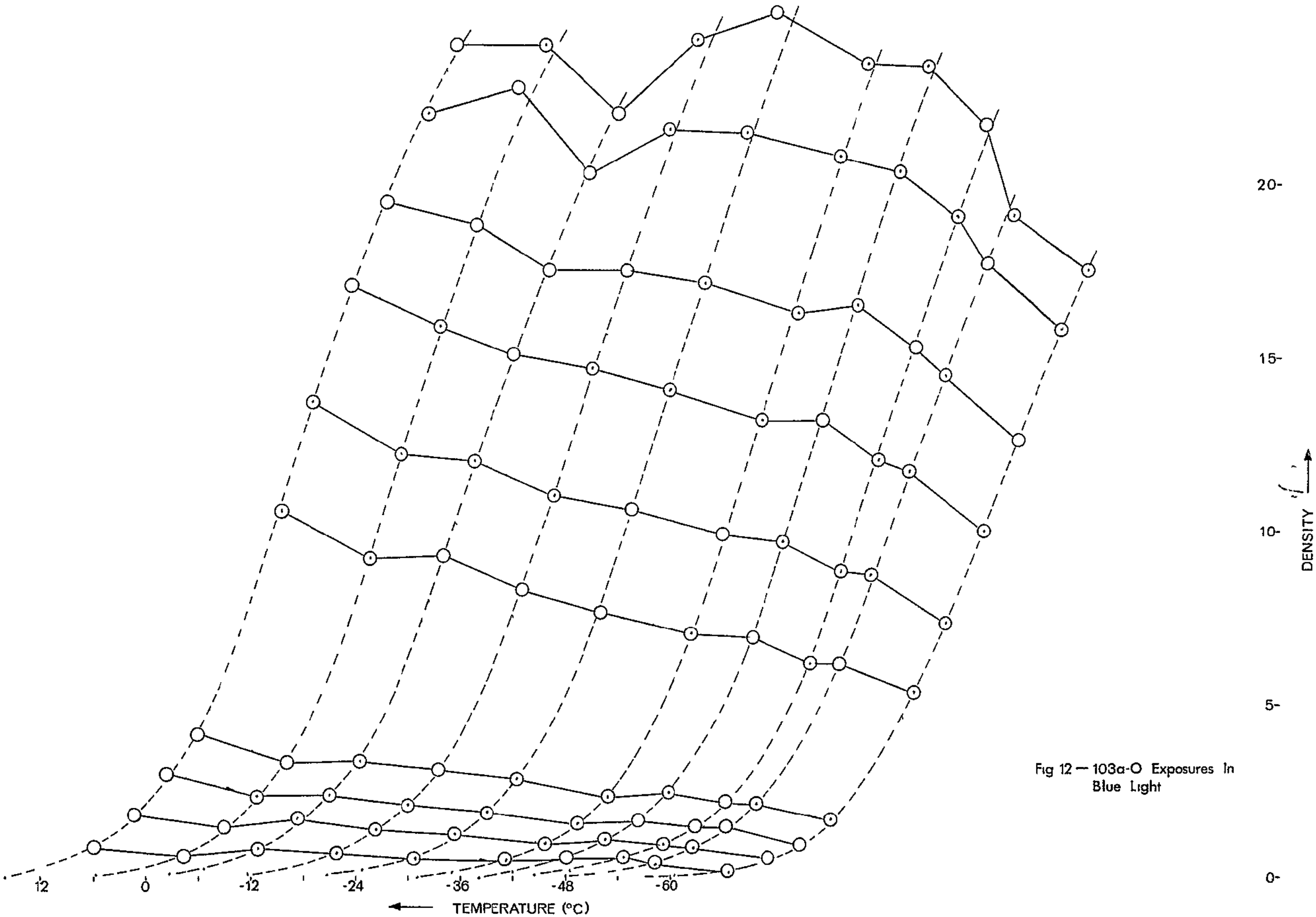


Fig 12 — 103a-O Exposures In Blue Light

temperature at which the exposure was made. The graphs therefore show the run of sensitivity (expressed as density) as a function of temperature in proper perspective at each value of log(I·t). The solid lines depict the change in sensitivity as a function of temperature for a constant (I·t), i.e. the same step.

V. DATA INTERPRETATION

Although in general the scatter in the data presented in Figures 5 through 12 is significant in the denser and fainter steps, the steps at intermediate density show a relatively smooth dependence of sensitivity upon platen temperature. In integrated light as well as blue and red light the Tri-X and Plus-X show a sensitivity maximum within the temperature range employed. The point of maximum is less well defined in the bright and faint steps than in the intermediate steps, but a trend to higher optimum temperatures for higher light levels seems apparent. This effect is best indicated in Figure 6 where the temperature of maximum density shifts from near -22°C for the fainter steps to the range of -6°C for the brighter steps. Of course the exact temperatures are impossible to determine from this data, but the trend seems fairly well established.

In neutral light the 103a-0 displays a nearly linear decrease in sensitivity with lower temperatures at all light levels. The same is true in the blue exposures in the faint and intermediate steps, but in the brighter steps a point of optimum density seems to appear. This is likely ficticious being due to scatter; however, if it is real, it would mean a reversal of the effect in the Plus-X and Tri-X. That is, the optimum temperature for the 103a-0 would be shifting to lower temperatures at higher light levels. However since the effect does not occur in neutral light it is likely due to scatter in the blue exposures. In any event it is readily apparent that the optimum temperature for 103a-0 at these light levels is above 16°C. Therefore for relatively high light levels and short exposure times it might prove advantageous to heat 103a-0 to its optimum temperature. An application to solar work is suggested. If one were interested in small scale resolution of Doppler velocity fields on the sun, one might try using heated 103a-0 on high resolution spectra on interesting lines in the blue region. The heated 103a-0 might allow very short exposures which could take advantage of moments of excellent seeing.

An interesting general effect is the way gamma varies under these conditions of exposure and temperature. If one defines gamma in the usual way as the tangent of the angle that the straight line portion of the characteristic curve makes with the log(I·t) axis, then it is approximately true that gamma is insensitive to temperature for the Tri-X and Plus-X. The result is obtained rather subjectively from noticing that the characteristic curves for Tri-X and Plus-X run approximately parallel in their straight line portions.

In the 103a-0 however, a noticeable difference of slope exists. If the quantity $\Delta D/\Delta \log(I \cdot t)$ is formed by counting squares in the straight line portion of the curves of 16°C and -56°C in Figure 7, relative values are found of 3.0 and 2.6. Therefore, the gamma of the 103a-0 slowly decreased with temperature as did the sensitivity. These values of gamma bear no relation to the published values of gamma for 103a-0 since my log(I·t) scale is relative and could be expanded or contracted arbitrarily.

A similar interpretation will result by considering a more general definition of gamma. Define gamma at any point on the characteristic curve as $\Delta D/\Delta \log(I\cdot t)$, i.e. not restrict it to the straight line portion. Convenient points to use are obviously those densities produced by the various steps in the wedge since their $\log(I\cdot t)$ relative values are known and the $\Delta \log(I\cdot t)$'s are constant between the same two steps for all equal exposures. We can therefore produce relative values of gamma merely by taking differences in density between adjacent steps. We can define a relative gamma as:

$$\gamma_{rel} = \frac{D_n - D_{n-1}}{\log(I\cdot t)_n - \log(I\cdot t)_{n-1}} = \frac{\Delta D}{\Delta \log(I\cdot t)} \quad \text{between adjacent steps}$$

where n is the step number from 2 to 12. Small values of n correspond to γ_{rel} at low light levels and high values of n correspond to γ_{rel} at high light levels. For a particular value of n and constant exposure, the value of $\log(I\cdot t)$ is also constant. Therefore the values of ΔD between adjacent steps are proportional to the values of γ_{rel}.

One can therefore see how γ_{rel} is acting at any point on any plot by noticing if the lines of constant $\log(I\cdot t)_{rel}$ value are getting closer together, getting further apart, or merely remaining constant. In just the straight line portions of the Tri-X and Plus-X curves the lines of constant $\log(I\cdot t)_{rel}$ follow each other closely. This indicates that γ_{rel} is remaining constant with temperature. In the straight line portion of the graphs for 103a-0 the constant $\log(I\cdot t)_{rel}$ lines tend to converge toward lower temperature indicating that γ_{rel} is decreasing. However, in the brighter steps of 103a-0 blue (Figure 12), γ_{rel} first increases and then decreases as the temperature decreases. Again this effect is probably not real, but is due to scatter.

Figures 5, 6, and 7 are the neutral exposures of Tri-X, Plus-X, and 103a-0. A strict comparison is not possible since the exposures were different and the 103a-0 is not sensitive to the longer wavelengths as is the Tri-X and Plus-X. They do however show the general effects discussed earlier, and serve as a check on the other exposures.

The exposures in red light on Tri-X and Plus-X were of equal times and intensities, thus permitting a more detailed comparison. First, it is readily noticed that the Tri-X is more sensitive than the Plus-X at all light levels, but more so at the fainter light levels than at the brighter ones. Since the exposures are equal in the two emulsions, the values of γ_{rel} can be directly compared and are just proportioned to the differences in density between adjacent steps. The values of γ_{rel} are greater in the Tri-X between steps 1 to 6 than they are in Plus-X. However they become equal or greater in the Plus-X between steps 7 to 12. This same effect occurs in varying degrees in comparisons of the blue exposures of Tri-X, Plus-X, and 103a-0, and to some extent in the neutral exposures. This effect can be better visualized by referring to a diagram like Figure 13. Emulsions A and B are two different emulsions exposed over the same log(I·t) range at the same temperature. Point P is that value of log(I·t) at which each emulsion produces the same density. In the case of the red exposures just described, Tri-X acts like emulsion A and Plus-X like emulsion B. Tri-X produces a higher density than Plus-X at all values of log(I·t) below point P. Tri-X begins with a much higher gamma than Plus-X but they soon become equal and the Plus-X gamma becomes greater before point P is reached. Indeed point P might never be reached with increasing log(I·t) if the characteristic curves had shoulders as indicated by the dashed lines. In the red exposures point P is never reached since the Tri-X produces higher densities at all light levels.

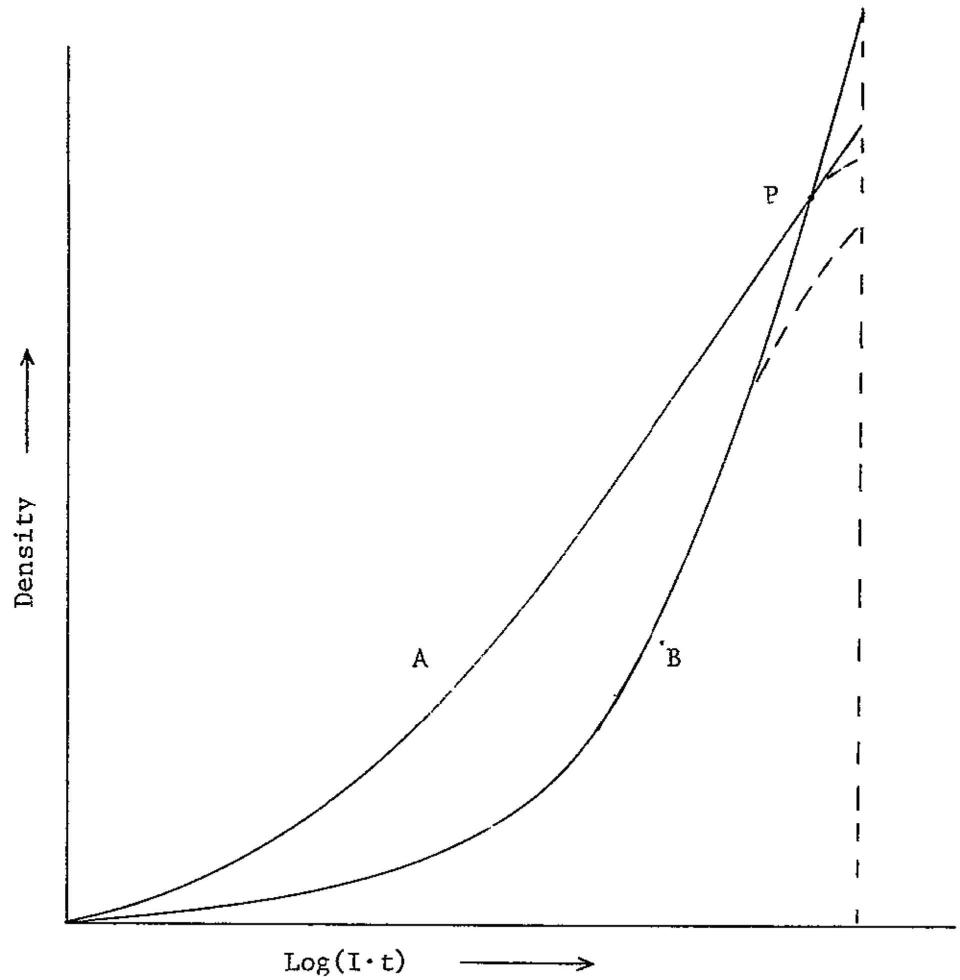


Fig. 13. -- The response of two emulsions with different gammas over the same log(I·t) range.

In the blue exposures of Tri-X and Plus-X an almost identical situation exists. Tri-X is more sensitive at all levels with a higher gamma than Plus-X in the toe region of the characteristic curve. In the brighter levels the Plus-X has a higher gamma just as in the red exposures, and point P is not reached.

The most interesting comparison is that between the blue exposures of Tri-X and 103a-O. At ambient temperature the toes of the characteristic curves are nearly the same, with Tri-X performing slightly better, i.e. γ_{rel} is a little higher. Response becomes equal at step #8 with 103a-0 having the higher γ_{rel} and out performing the Tri-X at the higher light levels. Tri-X is performing like emulsion A in Figure 13 and 103a-0 like emulsion B. Point P is reached at step #8. As the temperature is lowered the γ_{rel} for the Tri-X at low light levels increases tremendously to a corresponding maximum in response at approximately -29°C. However, the γ_{rel} and response of the 103a-0 decreases almost linearly. At the brighter levels the gamma for the Tri-X remains nearly constant. The 103a-0 probably suffers a slow decrease in γ_{rel} if the optimum near -22°C at high light level is not real, but due to scatter. At the lowest temperature point P has moved to a value of log(I·t) a little above step #12.

A rough check of this data can be made in a relative sort of way. The gammas of 103a-0 and Tri-X are published as a function of development time in Kodak Plates & Films for Science and Industry for ambient temperature and D-19 developer. If the ratio of $\gamma_{103a\text{-}0}/\gamma_{Tri\text{-}X}$ is formed for the proper development times a value of about 1.60 is found. For the ambient exposures in blue light for Tri-X and 103a-0 a ratio

$$\frac{\gamma_{rel}(103a\text{-}0)}{\gamma_{rel}(Tri\text{-}X)}$$

of 1.3 is found. The difference is not large and could be caused by at least two factors. First the 103a-0, although kept refrigerated, was several years old. If its response deteriorated, the ratio of gammas would decrease. Secondly, the developer was different, but the times and temperatures of development were the same. Acufine was used for the Tri-X and it likely produced a higher gamma than the D-19 would have.

The difference in the ratios is therefore neither extreme or unexpected, and conforms well with other published results.

One other comparison is important. If the blue exposures on Tri-X are carefully examined with respect to the red exposures on Tri-X, one notices that the temperature of optimum sensitivity is higher for the red than for the blue. A similar result is found for the red and blue exposures on Plus-X. Admittedly this effect is not as readily demonstrated as the others because of the scatter, but it likely exists.

An attempt is made in Figure 14 to show the general results of this investigation for a hypothetical emulsion. A family of characteristic curves are shown that differ only in the temperature at which the exposures were made. The temperature range brackets the optimum point for the emulsion. The point of optimum temperature is higher for higher light levels and the locus of optimum points shifts to higher temperature for longer wavelengths.

The three major effects of (1) sensitivity dependence on temperature, (2) optimum temperature dependence on light level, and (3) optimum temperature dependence on wavelength require theoretical explanation. Effects 1 and 2 are conveniently predictable or explainable by the Gurney-Mott theory of latent image formation. Only a brief description of the theory will be given here as many excellent references exist which describe the theory and its shortcomings in detail, for example see Mees (1954).

Basically the Gurney-Mott theory makes use of pure metallic silver as the substance of the latent image. The existance of sufficiently large numbers of displaced silver ions (interstitial) in the silver halide crystal is assumed. Silver sulfide and physical crystal defects

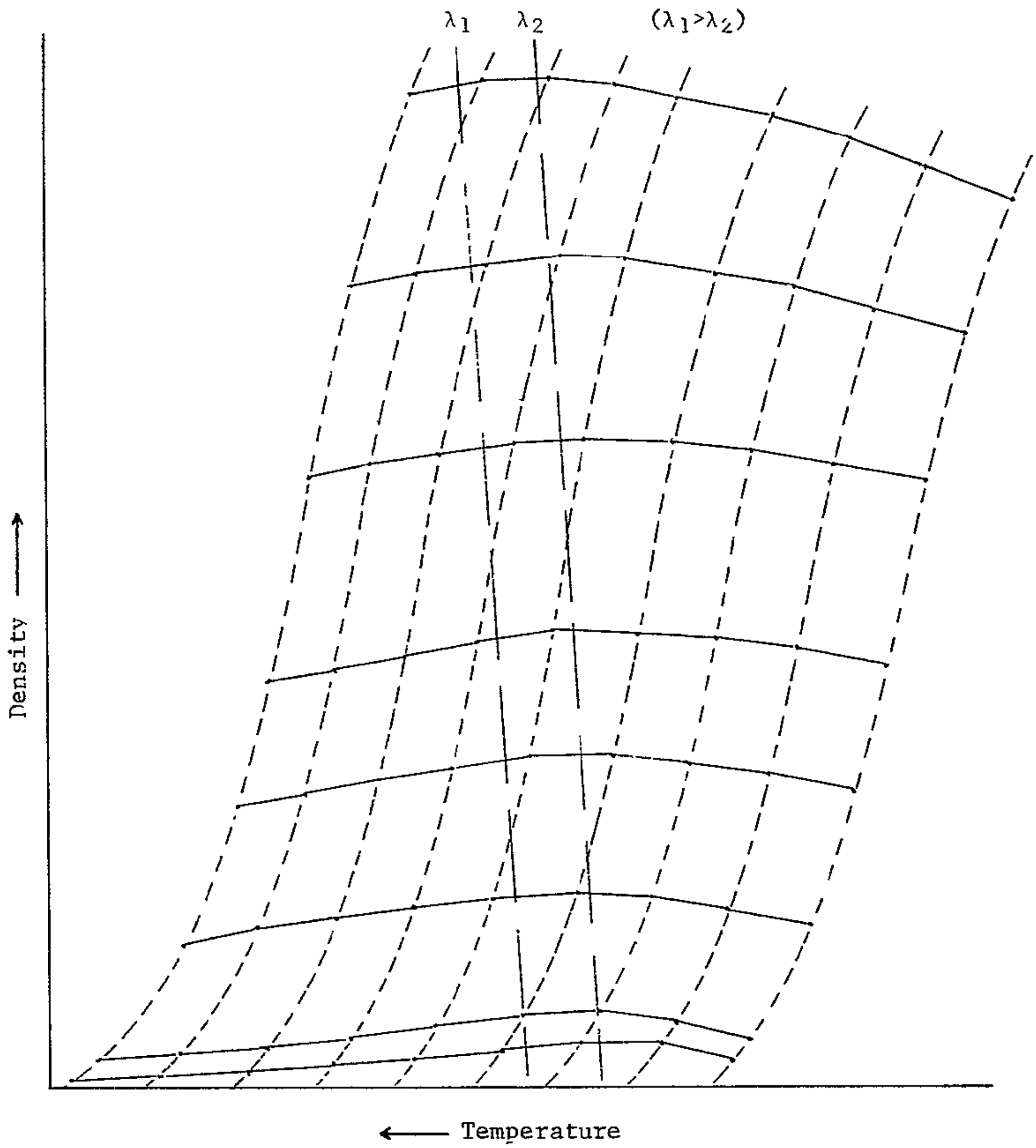


Fig. 14. -- Hypothetical response of an emulsion as a function of light level, color, and temperature in the region of its optimum temperature for the exposure conditions.

are "sensitivity specks" and can trap an electron that is moving freely in the conduction band of the crystal. Upon exposure of the silver halide to light, two processes are begun. One is electronic and occurs when a photon enters the crystal and imparts enough of its energy to an electron to raise its energy to that of the conduction band. The freely moving electron can lose a small amount of energy and get trapped on a "sensitivity speck". The ionic process then begins and consists of a nearby interstitial positive silver ion being attracted to the trapped negative electron. The silver ion deposits onto the "sensitivity speck" as pure silver and the process starts again. When enough silver atoms have built up on the "sensitivity speck", the crystal is capable of being rapidly reduced to silver by the action of the developer.

The dependence of sensitivity on temperature for a given light level can be shown by considering the rate of formation of the latent image. For a fixed intensity and wavelength, the rate of liberation of electrons in a crystal of silver halide is essentially constant being independent of temperature. However, the stability of a trapped electron is temperature dependent. Thermal motions can impart enough energy to the electron to free it from its trapped position. A lower temperature will therefore increase electron stability. On the other hand the migration of the silver ion is impeded by lower temperature. The motion of the silver ion has an opposite temperature dependence to that of electron stability. At some temperature the effects of the two processes will combine to produce the maximum response. The dependence of sensitivity on temperature at a given light level as shown by the data is indicative of the combination of these two processes.

One must go one step further to explain the shift of optimum temperature to higher values for higher light levels. Consider two light levels, one high and one low with exposures at low temperature. At the low intensity relatively few electrons are produced in the crystal. For the latent image to build efficiently, each trapped electron must be kept stable as long as possible. Ion motion is sluggish but the rate of latent image formation is dominated by the electron stability requirement. At high intensity a flood of electrons are produced. Once an electron is trapped it repels all others until neutralized by a silver ion. For the latent image to form efficiently, ion motion must be relatively higher than in the case of low intensity. One would therefore expect that high light levels would have higher optimum temperatures than low light levels due to the requirement of better ion mobility. This result is supported by the data for the Tri-X and Plus-X emulsions.

The least obvious effect in the data is the shift of optimum sensitivity to higher temperatures at all light levels for the red exposures as compared to the blue for both Tri-X and Plus-X. These emulsions contain sensitizing dyes to broaden their response from the blue through the red region of the spectrum. Evans (1942) studied the effect of temperature on the spectral response of sensitized emulsions. He found in general that low temperatures lowered the sensitivity of the sensitized region more than that of the blue region. In part the loss of sensitivity was due to the decreased absorption of light by the sensitizing dye at lower temperatures. In the blue exposures the optimum temperature is determined by the trade-offs of electron stability and ion mobility. The production of electrons in the crystal is rather insensitive to temperature. In the red exposures the same two effects operate, but the production of electrons is dependent on temperature due to the action of the sensitizing dyes. The red photons cannot be directly absorbed by the crystal as can blue photons, but must transfer their energy to the crystal by way of the sensitizing dye on the surface of the crystal. It is this latter process which at least in part causes the observed shift of optimum temperature to higher values for the red exposures.

VI. CONCLUSIONS

In an assessment of factors which could cause errors in the data, one might suspect that the largest error would occur in the temperature measurement due to the rather primative way the cooling was accomplished. However, it can be shown that this is not the case. First, it is extremely unlikely that any one H & D plot could be in error in temperature so greatly that it should have been plotted at the position of a neighboring curve at about ±10°C away. A difference of even ±5°C around the measured position would cause hardly a noticeable dip in lines of constant $\log(I \cdot t)_{rel}$. In this discussion of errors in the temperature measurement we are of course not referring to the difference in temperature between the platen and the actual temperature of the emulsion. The actual emulsion temperature might lag the platen temperature by as much as several degrees. The equilibrium condition between platen and emulsion is fixed by the processes of heat transfer. It is this equilibrium condition that was supposedly achieved in the actual exposures. In equilibrium the temperature of the emulsion would lag the platen temperature. The emulsion would also be in a region of high temperature gradient. An error in the temperature measurement therefore would correspond to making an exposure before the film came into equilibrium with the platen. The effect of this type of error should show up in the graphs as a shift of all the twelve points that define the H & D curve either up or down in density. An examination of the plots show that this type of shift almost never occurs. Therefore, the platen temperatures are rather dependable.

One does notice however, that there are several places where only the first six or last six points in a curve are shifted up or down in density. This seems suspiciously like an error in measuring the % transmissions in the wedge images since the scans were made in groups of six steps at a time. An inconsistant placement of the wedge image with respect to the slit of the microdensitometer would likely cause a systematic error. This is the most probable cause of the systematic shifts in the points along a characteristic curve, although care was taken to place the wedge image consistantly the same with respect to the slit.

Random scatter occurs in single points in various parts of the curves. These are more prominent at the higher density levels where the strip chart recording of transmission becomes very difficult to measure. At a transmission of 1% an error of .1% transforms into an error in density of .05. This is five small squares at the scale presented in Figures 5 through 12. At the low values of transmission, errors of several tenths of a percent are likely. The curves which show the change in response with temperature at the high light levels are therefore more uncertain than the curves for intermediate density.

Other factors which could cause scatter in the data are primarily local inhomogeneities in the emulsion and power surges that might effect the microdensitometer and chart recorder.

Errors that would cause an invalid comparison between emulsions or even within an emulsion include those systematic measurement errors previously discussed plus any change in the output of the lamp. However, the data was taken over a period of only three days which is a short time in the life of a good quality lamp. Lamp variation due to deterioration is therefore deemed insignificant. Of course a change in the lamp position would greatly affect the intensity at the wedge, but care was taken to insure that no relative motion occured.

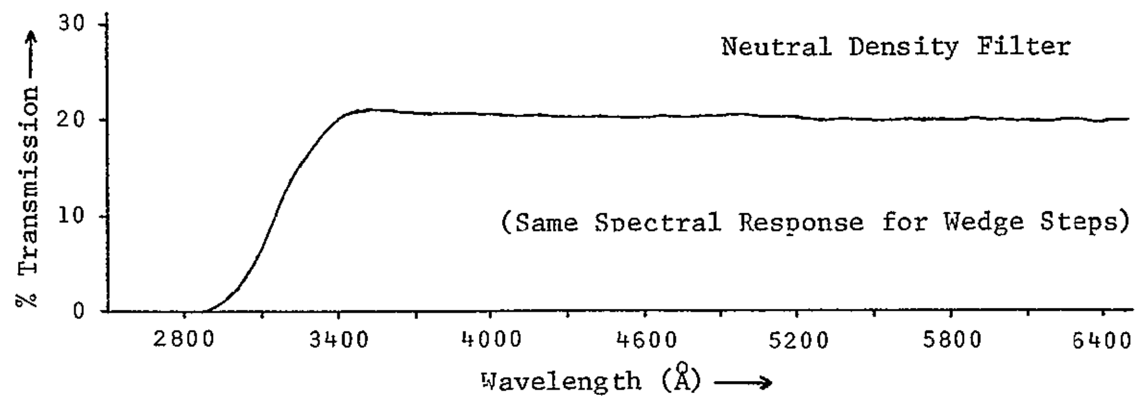
The effect of pressure on sensitivity has thus far been ignored. Hopefully in a relative study it would not be important, but this assumption may not be true. The lower pressure could affect the three emulsions differently. Lewis and James (1969) recently studied the effect of evacuation on low intensity reciprocity failure. They found that a fine grained silver halide emulsion when outgassed for 16 hours at a pressure $10^{-2}\mu$ showed virtually no low intensity reciprocity failure. If atmospheric pressure was restored with dry nitrogen after the outgassing period, low intensity reciprocity failure was still almost eliminated. When the nitrogen was replaced with either dry or wet oxygen, the sensitivity of the emulsion became much worse but did not get as low as the initial value before any evacuation. A possible explanation is that the oxygen forms O_2^- at the surface of the silver halide crystal, thus robbing it of some of its electrons that could otherwise be trapped on "sensitivity specks".

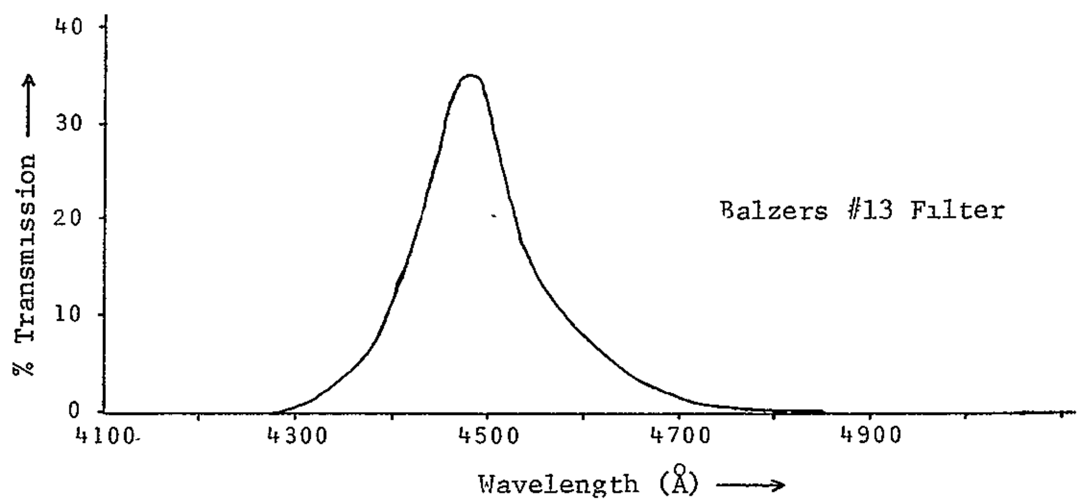
In the light of these results an omission in this study is obvious. A control exposure should have been made at atmospheric pressure in each color before the camera was evacuated. However, it is not likely that a measureable result could be found. The pressure at best was only on the order of 500μ -- 5×10^4 higher than that used by Lewis & James. At this pressure sufficient outgassing of the film would probably not occur in the two hours or so that it took to make the expsoures on one emulsion type.

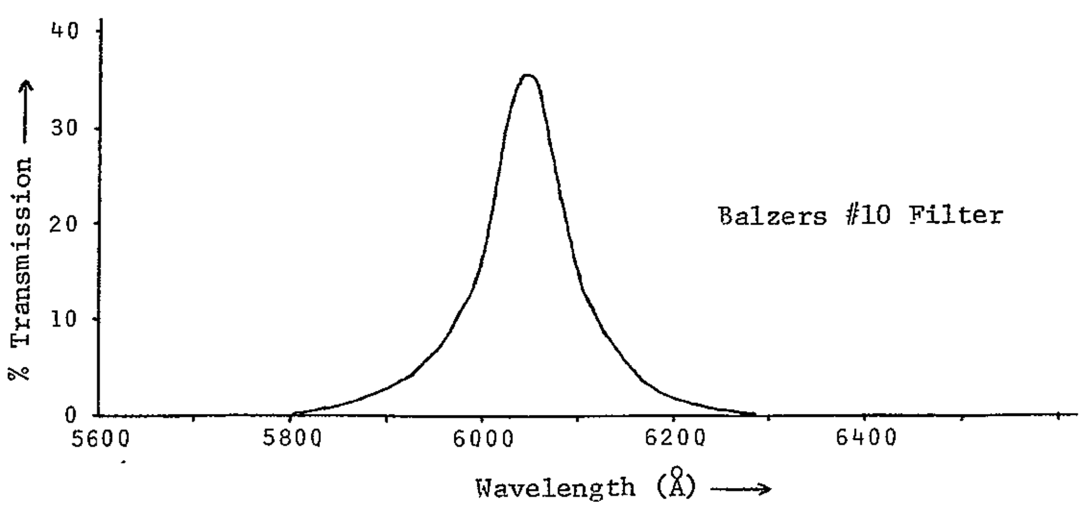
At optimum temperature and low intensities the Tri-X in blue light has better response than the 103a-0. However, the gamma of the 103a-0 in the linear portion of the characteristic curve is higher. It would be informative to be able to make the same type of comparison between these two emulsions at the same total exposure, but with the light level much lower so that the exposure times would be on the order of an hour. If the same type of low intensity response were found, it would mean that cooled Tri-X could be used to detect fainter blue sources than could be detected with 103a-0. However, the photometric properties would be better in the 103a-0. Since the gamma is higher for the 103a-0, greater density differences would result between stellar magnitudes allowing a more accurate magnitude determination to be made. Obviously one cannot know how the emulsions will respond to fainter and longer exposures until the tests are made. It is hoped that this study will help to determine how future studies might best be performed and evaluated.

APPENDIX

A. Filter Response







B. Exposure and Development

The light source was a Baush and Lomb tungsten lamp number 33-86-39 placed approximately six feet from the step wedge. It operated off of the secondary winding of a transformer rated at 8.0 amperes and 6.3 volts.

All film was in 35mm roll form. The 103a-0 was developed in D-19 for 3.75 minutes at 75°F. The Tri-X and Plus-X were developed in Acufine for 3.75 and 3.25 minutes respectfully at 75°F. All film was stopped for one minute and placed in Rapid-Fix for two minutes before being washed for 20 minutes. The following table gives the film type, emulsion number, filter arrangement, and exposure times for the various cases.

Film type and #	Filter arrangement	Exposure time (sec.)
103a-0 # SP702-169721	Opal Diffuser	30
	Balzers #13 plus 20% Neutral	15
Tri-X # 5063-416-14	Opal Diffuser plus 20% Neutral	30
	Balzers #13 plus 20% Neutral	15
	Balzers #10 plus 20% Neutral	5
Plus-X #5061-522-14	Opal Diffuser	30
	Balzers #13 plus 20% Neutral	15
	Balzers #10 plus 20% Neutral	5

C. Film Measurement Data

Tri-X 35mm Film   Neutral Filter   30 Sec. Exposure

Step Number	% Trans. of Fog	Total Trans.	% Trans. Above Fog	Density Above Fog
		Exposure 1	17.6°C	
1	33.4	33.4	100.0	0.000
2	↓	32.8	98.2	0.007
3	↓	30.8	92.2	0.035
4	↓	27.0	80.8	0.092
5	↓	23.5	70.4	0.152
6	↓	19.0	56.8	0.245
7	↓	5.00	14.95	0.824
8	↓	2.75	8.24	1.084
9	↓	1.40	4.18	1.378
10	↓	0.86	2.57	1.590
11	↓	0.53	1.59	1.798
12	↓	0.39	1.17	1.931
		Exposure 2	5.0°C	
1	34.0	33.6	98.8	0.005
2	↓	32.6	95.8	0.018
3	↓	30.0	88.3	0.054
4	↓	25.7	75.6	0.121
5	↓	20.7	60.9	0.215
6	↓	16.1	47.4	0.324
7	↓	4.10	12.05	0.919
8	↓	2.35	6.92	1.159
9	↓	1.30	3.83	1.416
10	↓	0.80	2.35	1.628
11	↓	0.51	1.50	1.823
12	↓	0.37	1.09	1.962
		Exposure 3	-3.7°C	
1	34.0	34.0	100.0	0.000
2	↓	32.3	94.7	0.023
3	↓	28.6	84.1	0.075
4	↓	22.0	64.7	0.189
5	↓	16.8	49.2	0.308
6	↓	12.3	36.2	0.442
7	33.5	3.92	11.7	0.931
8	↓	2.20	6.56	1.183
9	↓	1.33	3.97	1.401
10	↓	0.86	2.57	1.590
11	↓	0.55	1.64	1.785
12	↓	0.37	1.105	1.956

		Exposure 4	−13.5°C	
1	33.0	32.1	97.3	0.011
2	33.0	30.3	91.8	0.037
3	33.2	26.6	80.1	0.096
4	33.3	20.2	60.6	0.217
5	33.4	15.3	45.8	0.339
6	33.5	11.0	32.8	0.484
7	34.0	3.53	10.4	0.982
8	↓	2.00	5.88	1.230
9		1.20	3.53	1.452
10		0.78	2.29	1.640
11		0.53	1.56	1.806
12		0.392	1.150	1.939
		Exposure 5	−22.0°C	
1	33.7	32.5	96.5	0.015
2	33.9	30.8	90.8	0.041
3	34.3	26.9	78.5	0.105
4	34.7	20.3	58.5	0.232
5	35.0	16.0	45.7	0.340
6	35.4	11.8	33.3	0.477
7	34.2	3.04	9.00	1.045
8	34.4	1.90	5.68	1.245
9	34.6	1.20	3.57	1.447
10	34.8	0.79	2.27	1.643
11	35.0	0.51	1.46	1.835
12	35.2	0.39	1.11	1.954
		Exposure 6	−29.5°C	
1	33.2	31.9	96.1	0.017
2	33.3	29.2	87.6	0.058
3	33.3	24.5	73.5	0.133
4	33.4	17.4	52.1	0.283
5	33.5	14.5	43.3	0.363
6	33.6	10.8	32.2	0.492
7	33.8	3.24	9.58	1.018
8	33.6	1.96	5.84	1.233
9	33.5	1.16	3.46	1.460
10	33.4	0.78	2.34	1.630
11	33.2	0.53	1.59	1.798
12	33.0	0.43	1.30	1.886

Exposure 7 −38.0°C

1	34.5	34.0	98.5	0.006
2	34.2	32.0	93.6	0.028
3	34.0	27.6	81.2	0.090
4	33.8	21.0	62.1	0.206
5	33.4	16.0	47.9	0.319
6	33.0	11.4	34.6	0.460
7	34.5	4.00	11.6	0.935
8	34.2	2.55	7.46	1.127
9	33.8	1.47	4.35	1.361
10	33.3	0.88	2.64	1.578
11	32.8	0.53	1.62	1.790
12	32.5	0.39	1.20	1.920

Exposure 8 −47.0°C

1	32.7	32.0	97.8	0.009
2	32.8	30.2	92.1	0.035
3	32.9	26.8	81.5	0.088
4	33.0	21.5	65.1	0.186
5	33.1	17.0	51.4	0.289
6	33.2	13.0	39.2	0.406
7	33.8	3.63	10.7	0.970
8	↓	2.35	6.95	1.158
9		1.41	4.17	1.379
10		0.94	2.78	1.555
11		0.59	1.75	1.756
12		0.47	1.39	1.856

Exposure 9 −55.5°C

1	32.6	32.0	98.1	0.008
2	32.7	30.0	91.7	0.037
3	32.8	27.5	83.8	0.076
4	32.8	22.4	68.3	0.165
5	32.9	19.0	57.8	0.238
6	33.0	14.0	42.4	0.372
7	32.8	4.50	13.7	0.863
8	↓	2.90	8.84	1.053
9		1.80	5.48	1.261
10		1.08	3.29	1.482
11		0.78	2.48	1.605
12		0.63	1.92	1.716

Plus-X 35mm Film   Neutral Filter   30 Sec. Exposure

Step Number	% Trans. of Fog	Total Trans.	% Trans. Above Fog	Density Above Fog
		Exposure 1	17.8°C	
1	43.5	43.5	100.0	0.000
2	43.4	40.0	92.1	0.035
3	43.2	35.0	81.0	0.091
4	43.0	27.5	64.0	0.193
5	42.9	22.2	51.7	0.286
6	42.8	17.0	39.7	0.401
7	43.7	4.16	9.51	1.021
8	43.6	2.30	5.27	1.278
9	43.4	1.18	2.72	1.565
10	43.2	0.69	1.60	1.795
11	42.9	0.45	1.05	1.978
12	42.8	0.37	0.86	2.063
		Exposure 2	5.8°C	
1	44.8	43.8	98.0	0.008
2	44.7	40.5	90.6	0.042
3	44.5	34.0	76.5	0.116
4	44.3	25.5	58.9	0.229
5	44.0	19.2	43.6	0.360
6	43.8	13.9	31.8	0.497
7	44.7	3.65	8.17	1.087
8	44.6	2.08	4.66	1.331
9	44.4	1.12	2.52	1.598
10	44.0	0.65	1.48	1.829
11	43.6	0.45	1.03	1.987
12	43.4	0.37	0.85	2.068
		Exposure 3	-5.0°C	
1	44.0	42.2	95.8	0.018
2	43.9	37.8	86.1	0.064
3	43.8	30.2	69.0	0.161
4	43.6	21.5	49.3	0.307
5	43.4	15.8	36.4	0.438
6	43.2	11.2	25.9	0.586
7	43.5	3.04	6.99	1.155
8	43.4	1.77	4.08	1.389
9	43.2	1.02	2.36	1.627
10	43.1	0.63	1.46	1.835
11	43.0	0.39	0.91	2.040
12	42.8	0.29	0.68	2.167

Exposure 4 $-14.6°C$

1	44.2	41.9	94.7	0.023
2	↓	36.0	81.4	0.089
3	↓	28.2	63.8	0.195
4	↓	20.0	45.3	0.343
5	↓	14.5	32.8	0.484
6	↓	10.8	24.4	0.612
7	43.3	2.68	6.19	1.208
8	43.3	1.69	3.91	1.407
9	43.2	1.02	2.36	1.627
10	43.2	0.67	1.55	1.809
11	43.0	0.47	1.09	1.962
12	43.0	0.37	0.86	2.065

Exposure 5 $-22.0°C$

1	43.5	40.0	92.0	0.036
2	43.7	34.7	79.4	0.100
3	43.9	27.5	62.6	0.203
4	44.1	19.0	43.1	0.365
5	44.2	13.9	31.5	0.501
6	44.3	9.80	22.1	0.655
7	43.0	2.70	6.28	1.202
8	43.1	1.57	3.64	1.438
9	43.2	0.96	2.22	1.653
10	43.3	0.61	1.41	1.850
11	43.4	0.47	1.08	1.966
12	43.4	0.37	0.85	2.068

Exposure 6 $-29.5°C$

1	43.5	40.0	92.0	0.036
2	43.8	35.0	80.0	0.096
3	44.1	27.9	63.2	0.199
4	44.4	19.6	44.1	0.355
5	44.8	14.7	32.8	0.484
6	45.0	10.6	23.6	0.627
7	43.8	2.80	6.39	1.194
8	43.9	1.75	3.99	1.399
9	44.0	1.08	2.45	1.610
10	44.0	0.80	1.82	1.739
11	44.1	0.61	1.38	1.860
12	44.2	0.53	1.20	1.920

Exposure 7 -38.0°C

1	43.6	40.0	91.6	0.038
2	43.8	35.0	79.9	0.097
3	44.0	27.8	63.2	0.199
4	44.3	20.2	45.6	0.341
5	44.6	15.4	34.6	0.460
6	44.8	11.7	26.1	0.583
7	43.8	2.88	6.58	1.181
8	44.0	1.87	4.25	1.371
9	44.2	1.16	2.62	1.581
10	44.4	0.82	1.85	1.732
11	44.8	0.65	1.45	1.838
12	44.9	0.63	1.40	1.853

Exposure 8 -46.0°C

1	43.0	39.0	90.6	0.042
2		34.6	80.5	0.094
3		28.3	65.8	0.181
4		21.0	48.9	0.310
5		16.0	37.2	0.429
6		12.2	28.4	0.546
7	42.6	3.60	8.45	1.073
8	42.5	2.31	5.43	1.265
9	42.4	1.51	3.56	1.448
10	42.3	1.06	2.51	1.600
11	42.2	0.804	1.91	1.720
12	42.1	0.667	1.56	1.800

Exposure 9 -54.7°C

1	44.5	40.8	91.6	0.038
2	44.3	36.2	81.7	0.087
3	44.2	30.1	68.1	0.166
4	44.1	22.8	51.8	0.285
5	44.0	17.4	39.6	0.402
6	43.9	13.1	29.8	0.525
7	44.8	4.28	9.55	1.019
8	44.7	2.75	6.17	1.209
9	44.5	1.76	3.96	1.402
10	44.4	1.22	2.75	1.560
11	44.2	0.94	2.13	1.671
12	44.0	0.78	1.77	1.752

103a-0 35mm Film Neutral Filter 30 Sec. Exposure

Step Number	% Trans. of Fog	Total Trans.	% Trans. Above Fog	Density Above Fog
		Exposure 1	16°C	
1	31.0	31.0	100.0	0.000
2	↓	30.5	98.5	0.007
3	↓	29.5	95.2	0.021
4	↓	27.5	88.7	0.053
5	↓	25.0	80.6	0.093
6	↓	21.0	67.8	0.169
7	↓	7.75	25.0	0.602
8	↓	4.10	13.2	0.876
9	↓	1.90	6.10	1.223
10	↓	0.93	3.00	1.522
11	↓	0.47	1.51	1.821
12	↓	0.353	1.14	1.943
		Exposure 2	6.2°C	
1	31.5	31.5	100.0	0.000
2	↓	31.5	100.0	0.000
3	↓	30.0	95.3	0.020
4	↓	28.7	88.0	0.055
5	↓	26.0	82.6	0.083
6	↓	23.0	73.0	0.136
7	↓	9.50	30.2	0.519
8	↓	5.30	16.8	0.774
9	↓	2.50	7.94	1.100
10	↓	1.20	3.81	1.419
11	↓	0.55	1.75	1.756
12	↓	0.373	1.15	1.926
		Exposure 3	-3.5°C	
1	31.8	31.0	97.5	0.010
2	31.5	30.5	96.8	0.014
3	31.3	30.0	95.8	0.018
4	31.1	28.0	90.0	0.045
5	30.9	25.2	81.5	0.088
6	30.7	22.3	72.6	0.139
7	30.8	10.2	33.1	0.480
8	30.7	5.90	19.2	0.716
9	30.6	2.75	9.00	1.045
10	30.4	1.30	4.28	1.368
11	30.2	0.59	1.95	1.709
12	30.0	0.373	1.24	1.906

Exposure 4 -10.0°C

1	31.5	31.5	100.0	0.000
2	31.4	31.0	98.6	0.006
3	31.3	29.5	94.4	0.025
4	31.2	28.0	89.8	0.046
5	31.1	26.0	83.6	0.077
6	31.0	23.5	75.8	0.120
7	31.3	11.0	35.2	0.453
8	31.2	6.60	21.2	0.673
9	31.1	3.20	10.3	0.987
10	31.0	1.50	4.84	1.315
11	30.9	0.647	2.10	1.677
12	30.8	0.373	1.21	1.917

Exposure 5 -20.5°C

1	31.0	30.5	98.5	0.006
2		30.5	98.5	0.006
3		29.4	94.8	0.023
4		28.5	91.8	0.037
5		27.0	87.1	0.059
6		25.2	81.3	0.089
7		11.8	38.1	0.419
8		7.50	24.2	0.616
9		3.82	12.3	0.910
10		1.96	6.32	1.199
11		0.882	2.84	1.546
12	↓	0.550	1.77	1.752

Exposure 6 -31.0°C

1	31.0	31.0	100.0	0.000
2		30.5	98.4	0.006
3		30.0	96.8	0.014
4		29.0	93.6	0.028
5		27.5	88.8	0.051
6		25.5	82.2	0.085
7		12.7	41.0	0.387
8		8.43	27.2	0.565
9		4.52	14.5	0.838
10		2.35	7.60	1.119
11		1.04	3.36	1.473
12	↓	0.63	2.03	1.692

Exposure 7 -38.0°C

1	30.8	30.8	100.0	0.000
2	30.6	30.0	98.0	0.008
3	30.4	30.0	98.6	0.006
4	30.2	29.0	96.1	0.017
5	30.0	27.0	90.0	0.045
6	30.0	24.2	80.6	0.093
7	30.6	14.0	45.7	0.340
8	30.5	8.90	29.2	0.534
9	30.4	4.80	15.8	0.801
10	30.2	2.45	8.12	1.090
11	30.0	1.06	3.54	1.450
12	29.8	0.53	1.78	1.749

Exposure 8 -44.5°C

1	30.0	30.0	100.0	0.000
2		30.0	100.0	0.000
3		29.5	98.4	0.007
4		29.0	96.6	0.015
5		27.0	90.0	0.045
6		25.5	85.0	0.070
7		13.9	46.3	0.334
8		9.40	31.3	0.504
9		5.10	17.0	0.769
10		2.75	9.16	1.038
11		1.20	4.00	1.397
12	↓	0.726	2.42	1.616

Exposure 9 -48.0°C

1	30.0	30.0	100.0	0.000
2		30.0	100.0	0.000
3		30.0	100.0	0.000
4		29.0	96.6	0.015
5		28.0	93.4	0.029
6		26.0	86.6	0.062
7		14.5	48.4	0.315
8		10.0	33.3	0.477
9		5.70	19.0	0.721
10		3.14	10.5	0.978
11		1.53	5.10	1.292
12	↓	0.98	3.27	1.485

Exposure 10 -55.5°C

1	31.0	31.0	100.0	0.000
2	↓	31.0	100.0	0.000
3		31.0	100.0	0.000
4		30.0	96.7	0.014
5		28.0	90.3	0.044
6		27.0	87.0	0.061
7		16.2	52.3	0.281
8		11.3	36.5	0.438
9		6.50	21.0	0.678
10		3.70	11.9	0.924
11		1.66	5.35	1.272
12		1.18	3.81	1.419

Tri-X 35mm Film Red Filter 5 Sec. Exposure

Step Number	% Trans. of Fog	Total Trans.	% Trans. Above Fog	Density Above Fog
		Exposure 1	17.6°C	
1	34.4	31.9	92.7	0.032
2	33.9	26.2	77.4	0.111
3	33.7	19.0	56.4	0.248
4	33.4	11.2	33.6	0.473
5	33.2	7.40	22.3	0.651
6	33.0	5.30	16.1	0.793
7	34.6	1.68	4.86	1.313
8	34.3	1.08	3.15	1.501
9	34.0	0.63	1.85	1.732
10	33.6	0.43	1.28	1.982
11	33.2	0.216	0.65	2.187
12	32.9	0.120	0.36	2.440
		Exposure 2	4.6°C	
1	33.8	30.5	90.3	0.044
2	33.6	23.9	71.2	0.147
3	33.4	16.6	49.7	0.303
4	33.2	10.0	30.1	0.521
5	33.0	5.90	17.9	0.747
6	32.8	4.20	12.8	0.892
7	34.0	1.37	4.03	1.394
8	34.0	0.86	2.53	1.596
9	33.8	0.63	1.87	1.728
10	33.7	0.41	1.22	1.913
11	33.6	0.196	0.53	2.270
12	33.5	0.120	0.35	2.455
		Exposure 3	-4.2°C	
1	33.4	28.8	86.3	0.063
2	33.6	21.8	64.9	0.187
3	33.9	14.2	41.9	0.377
4	34.2	8.40	24.6	0.609
5	34.5	5.70	16.5	0.782
6	34.8	4.10	11.8	0.928
7	33.5	1.33	3.97	1.401
8	33.7	0.88	2.61	1.583
9	33.9	0.59	1.74	1.759
10	34.1	0.37	1.09	1.964
11	34.4	0.275	0.82	2.086
12	34.6	0.196	0.58	2.236

		Exposure 4	−14.5°C	
1	34.0	29.8	87.6	0.057
2	↓	22.5	66.2	0.179
3	↓	15.8	46.5	0.332
4	↓	9.50	28.0	0.552
5	↓	6.90	20.3	0.692
6	↓	5.00	14.7	0.832
7	↓	1.45	4.27	1.369
8	↓	1.04	3.06	1.514
9	↓	0.73	2.15	1.667
10	↓	0.55	1.62	1.790
11	↓	0.353	1.04	1.985
12	↓	0.270	0.80	2.099
		Exposure 5	−22.3°C	
1	32.4	27.9	85.5	0.068
2	32.2	20.9	65.0	0.187
3	32.1	14.0	43.6	0.360
4	32.0	9.00	28.1	0.551
5	31.9	5.60	17.6	0.754
6	31.8	4.20	13.2	0.879
7	31.7	1.37	4.32	1.364
8	↓	0.883	2.88	1.540
9	↓	0.590	1.86	1.730
10	↓	0.432	1.36	1.866
11	↓	0.314	0.99	2.004
12	↓	0.216	0.68	2.167
		Exposure 6	−29.5°C	
1	31.8	27.4	86.2	0.064
2	32.0	21.1	66.0	0.180
3	32.3	14.6	45.2	0.344
4	32.5	9.00	27.7	0.557
5	32.8	6.00	18.3	0.737
6	33.0	4.60	13.9	0.856
7	32.2	1.47	4.56	1.341
8	32.4	0.96	2.96	1.528
9	32.6	0.59	1.81	1.742
10	32.8	0.37	1.16	1.935
11	33.0	0.26	0.79	2.102
12	33.4	0.20	0.60	2.221

		Exposure 7	−38.0°C	
1	32.2	28.0	87.0	0.060
2		22.0	68.4	0.164
3		15.5	48.2	0.316
4		9.70	30.1	0.521
5		6.30	19.6	0.707
6		4.90	15.2	0.818
7		1.80	5.59	1.252
8		1.22	3.79	1.421
9		0.78	2.42	1.616
10		0.55	1.71	1.767
11		0.37	1.15	1.939
12	↓	0.27	0.84	2.075
		Exposure 8	−46.0°C	
1	32.8	29.5	90.0	0.045
2	32.7	24.0	73.4	0.134
3	32.5	17.4	53.6	0.270
4	32.4	11.2	34.6	0.460
5	32.2	7.30	22.7	0.643
6	32.0	5.50	17.2	0.764
7	33.5	2.20	6.66	1.176
8	33.2	1.47	4.43	1.353
9	33.0	0.92	2.79	1.554
10	32.7	0.61	1.87	1.729
11	32.2	0.39	1.21	1.917
12	32.0	0.29	0.91	2.043
		Exposure 9	−51.5°C	
1	32.3	30.0	91.8	0.037
2	32.5	25.5	78.5	0.105
3	32.7	19.2	58.7	0.231
4	32.8	13.0	39.6	0.402
5	33.0	9.80	29.7	0.527
6	33.1	7.20	21.8	0.661
7	32.7	2.16	6.60	1.180
8	32.8	1.41	4.30	1.366
9	32.9	0.94	2.86	1.543
10	33.0	0.63	1.91	1.718
11	33.1	0.47	1.42	1.847
12	33.2	0.37	1.12	1.952

Plus-X 35mm Film   Red Filter   5 Sec. Exposure

Step Number	% Trans. of Fog	Total Trans.	% Trans. Above Fog	Density Above Fog
		Exposure 1	17.8°C	
1	44.8	44.8	100.0	0.000
2	45.0	44.0	97.8	0.009
3	45.1	42.8	95.0	0.022
4	45.2	39.0	86.4	0.063
5	45.4	35.8	78.9	0.102
6	45.5	31.8	70.0	0.154
7	44.6	11.2	25.2	0.598
8	44.7	5.84	13.1	0.882
9	44.8	2.74	6.12	1.213
10	44.9	1.53	3.41	1.467
11	45.0	0.82	1.82	1.739
12	45.0	0.63	1.40	1.853
		Exposure 2	5.3°C	
1	44.8	44.8	100.0	0.000
2		43.2	98.6	0.006
3		40.5	90.4	0.043
4		36.0	80.3	0.095
5		31.9	71.2	0.147
6	↓	27.0	60.3	0.219
7	43.5	9.10	20.9	0.679
8	43.6	4.81	11.05	0.956
9	43.7	2.35	5.38	1.269
10	43.8	1.35	3.08	1.511
11	44.0	0.75	1.71	1.767
12	44.0	0.59	1.34	1.872
		Exposure 3	-5.8°C	
1	44.0	43.5	99.0	0.004
2		42.0	95.5	0.019
3		39.0	88.7	0.052
4		35.0	79.6	0.099
5		30.6	69.5	0.158
6		26.0	59.1	0.228
7		8.15	18.5	0.732
8		4.50	10.2	0.991
9		2.34	5.32	1.274
10		1.39	3.16	1.500
11		0.82	1.88	1.726
12	↓	0.62	1.48	1.829

Exposure 4 -14.3°C

1	44.7	44.0	98.5	0.006
2	44.5	41.0	92.1	0.035
3	44.4	38.8	87.5	0.057
4	44.2	33.5	76.0	0.119
5	44.0	29.2	66.4	0.177
6	43.8	24.8	56.6	0.247
7	44.0	8.43	19.2	0.716
8	44.0	4.70	10.7	0.970
9	43.8	2.47	5.64	1.248
10	43.7	1.51	3.46	1.460
11	43.6	0.88	2.02	1.694
12	43.5	0.65	1.50	1.825

Exposure 5 -21.5°C

1	44.4	43.0	96.9	0.013
2	44.2	42.0	95.0	0.022
3	44.1	39.0	88.5	0.053
4	44.0	33.0	75.0	0.124
5	44.0	29.0	65.9	0.181
6	44.0	24.4	55.5	0.255
7	43.0	8.13	18.9	0.723
8	↓	4.47	10.4	0.982
9	↓	2.31	5.37	1.270
10	↓	1.35	3.14	1.503
11	↓	0.78	1.82	1.741
12	↓	0.63	1.47	1.833

Exposure 6 -29.0°C

1	44.4	44.4	100.0	0.000
2	44.2	42.1	99.8	0.000
3	44.0	39.0	88.6	0.052
4	43.7	33.2	73.6	0.133
5	43.3	28.8	66.5	0.177
6	43.1	24.6	57.1	0.243
7	43.9	8.76	20.0	0.698
8	43.8	4.95	11.3	0.946
9	43.5	2.60	5.98	1.223
10	43.3	1.49	3.44	1.463
11	42.8	0.82	1.92	1.717
12	42.5	0.63	1.48	1.829

Exposure 7 -38.0°C

1	45.7	44.9	98.4	0.007
2	45.6	43.6	95.6	0.019
3	45.4	41.0	90.4	0.043
4	45.2	36.2	80.2	0.095
5	45.0	31.8	70.7	0.150
6	44.8	27.0	60.3	0.219
7	45.6	11.3	24.8	0.605
8	45.4	6.60	14.55	0.837
9	45.2	3.90	8.62	1.064
10	44.8	2.18	4.87	1.312
11	44.5	1.38	3.10	1.508
12	44.1	1.08	2.45	1.610

Exposure 8 -46.5°C

1	44.0	43.0	97.7	0.008
2		41.6	94.5	0.024
3		38.8	88.3	0.054
4		35.4	80.5	0.094
5		31.9	72.5	0.139
6		28.2	64.1	0.193
7		12.2	27.8	0.555
8		7.46	16.95	0.770
9		4.10	9.32	1.030
10		2.53	5.75	1.240
11		1.51	3.43	1.464
12	↓	1.20	2.73	1.563

Exposure 9 -54.7°C

1	43.5	43.0	98.9	0.004
2	43.4	41.5	93.4	0.029
3	43.3	38.5	88.9	0.051
4	43.2	34.6	80.0	0.096
5	43.1	31.0	71.9	0.143
6	43.0	27.1	63.0	0.200
7	43.2	12.2	28.3	0.548
8		7.10	16.45	0.783
9		3.83	8.87	1.052
10		2.26	5.24	1.280
11		1.30	3.01	1.521
12	↓	1.04	2.41	1.617

Tri-X 35mm Film   Blue Filter   15 Sec. Exposure

Step Number	% Trans. of Fog	Total Trans.	% Trans. Above Fog	Density Above Fog
		Exposure 1	17.6°C	
1	33.0	32.6	98.7	0.005
2	↓	32.2	94.5	0.024
3	↓	27.0	81.8	0.087
4	↓	20.0	60.6	0.217
5	↓	14.0	42.4	0.372
6	↓	9.80	29.7	0.527
7	↓	2.30	6.97	1.156
8	↓	1.37	4.15	1.381
9	↓	0.94	2.85	1.545
10	↓	0.686	2.06	1.686
11	↓	0.470	1.43	1.845
12	↓	0.370	1.12	1.950
		Exposure 2	4.6°C	
1	33.8	33.1	98.0	0.008
2	33.8	30.4	90.0	0.045
3	33.7	25.8	76.5	0.116
4	33.7	18.0	53.4	0.272
5	33.6	12.4	36.9	0.432
6	33.5	8.40	25.1	0.600
7	33.4	2.06	6.17	1.209
8	↓	1.33	3.98	1.400
9	↓	0.82	2.46	1.609
10	↓	0.59	1.77	1.752
11	↓	0.37	1.11	1.954
12	↓	0.27	0.81	2.091
		Exposure 3	-4.8°C	
1	33.0	31.3	94.9	0.022
2	33.2	27.6	83.2	0.079
3	33.2	21.8	65.6	0.183
4	33.3	14.5	43.6	0.360
5	33.4	9.70	29.0	0.537
6	33.5	6.90	20.6	0.686
7	↓	1.90	5.67	1.246
8	↓	1.27	3.79	1.421
9	↓	0.785	2.34	1.630
10	↓	0.570	1.70	1.769
11	↓	0.390	1.17	1.933
12	↓	0.333	0.995	2.000

Exposure 4 -14.5°C

1	35.5	32.7	92.2	0.035
2	35.1	28.1	80.1	0.096
3	34.6	21.5	62.2	0.206
4	34.0	14.0	41.2	0.385
5	33.5	8.90	26.6	0.575
6	33.0	6.20	18.8	0.725
7	35.4	2.30	6.50	1.187
8	35.0	1.45	4.14	1.383
9	34.5	0.96	2.78	1.555
10	33.9	0.686	2.02	1.694
11	33.3	0.430	1.29	1.889
12	32.8	0.294	0.90	2.050

Exposure 5 -22.3°C

1	34.2	32.6	95.3	0.020
2	34.0	27.7	81.5	0.088
3	33.8	21.8	64.5	0.190
4	33.6	14.0	41.7	0.379
5	33.3	8.90	26.8	0.571
6	33.0	6.10	18.5	0.732
7	33.8	1.80	5.33	1.273
8	33.5	1.14	3.51	1.454
9	33.2	0.765	2.31	1.636
10	33.0	0.550	1.67	1.777
11	32.7	0.350	1.07	1.970
12	32.4	0.290	0.74	2.130

Exposure 6 -29.5°C

1	34.0	32.0	94.2	0.025
2	33.8	27.5	81.4	0.089
3	33.6	20.5	61.0	0.214
4	33.4	13.4	40.2	0.395
5	33.1	8.50	25.7	0.590
6	32.9	5.80	17.6	0.754
7	34.1	2.26	6.63	1.178
8	34.0	1.55	4.56	1.341
9	33.8	0.98	2.90	1.537
10	33.5	0.705	2.10	1.677
11	33.2	0.450	1.35	1.869
12	33.0	0.314	0.95	2.022

Exposure 7 -38.0°C

1	33.9	31.5	92.9	0.031
2	33.5	27.0	80.6	0.093
3	33.1	20.5	62.0	0.207
4	32.8	13.4	40.8	0.389
5	32.3	8.60	26.6	0.575
6	32.0	6.20	19.4	0.712
7	34.0	2.10	6.18	1.209
8	33.7	1.37	4.07	1.390
9	33.2	0.88	2.66	1.575
10	32.7	0.59	1.81	1.742
11	32.0	0.37	1.16	1.935
12	31.5	0.27	0.86	2.068

Exposure 8 -46.5°C

1	32.5	30.2	93.0	0.031
2	32.6	26.2	80.4	0.094
3	32.8	19.8	60.3	0.219
4	33.0	13.2	40.0	0.397
5	33.2	9.6	28.9	0.539
6	33.3	7.0	21.0	0.677
7	33.0	2.06	6.25	1.204
8	↓	1.37	4.16	1.380
9	↓	0.90	2.73	1.563
10	↓	0.608	1.84	1.735
11	↓	0.470	1.43	1.844
12	↓	0.370	1.12	1.950

Exposure 9 -52.5°C

1	33.2	31.0	93.4	0.029
2	33.2	27.0	81.4	0.089
3	33.1	22.2	67.1	0.173
4	33.1	16.0	48.4	0.315
5	33.0	10.6	32.1	0.493
6	32.9	8.10	24.6	0.609
7	33.0	2.45	7.44	1.128
8	32.9	1.76	5.35	1.271
9	32.8	1.18	3.60	1.443
10	32.7	0.90	2.75	1.560
11	32.6	0.63	1.93	1.714
12	32.5	0.47	1.45	1.838

Plus-X 35mm Film   Blue Filter   15 Sec. Exposure

Step Number	% Trans. of Fog	Total Trans.	% Trans. Above Fog	Density Above Fog
		Exposure 1	17.8°C	
1	45.2	45.2	100.0	0.000
2	45.0	44.5	98.9	0.004
3	44.9	43.2	96.1	0.017
4	44.8	41.5	92.6	0.033
5	44.6	38.0	85.2	0.069
6	44.5	33.4	75.1	0.124
7	44.3	13.7	30.9	0.510
8	44.2	7.90	17.9	0.747
9	44.0	4.10	9.31	1.031
10	43.8	2.35	5.36	1.270
11	43.6	1.28	2.94	1.531
12	43.4	0.902	2.06	1.686
		Exposure 2	6.2°C	
1	44.6	44.6	100.0	0.000
2	44.4	43.2	97.3	0.011
3	44.2	41.0	92.7	0.032
4	43.8	38.0	87.7	0.057
5	43.4	33.3	76.3	0.117
6	43.0	29.0	67.5	0.170
7	44.8	10.5	23.4	0.630
8	44.7	5.93	13.3	0.876
9	44.6	3.18	7.14	1.146
10	44.4	1.92	4.33	1.363
11	44.2	1.08	2.44	1.612
12	44.0	0.78	1.77	1.752
		Exposure 3	-5.3°C	
1	43.8	43.8	100.0	0.000
2	43.8	43.0	98.2	0.007
3	43.8	40.5	92.5	0.033
4	43.9	36.5	83.1	0.080
5	43.9	32.4	73.8	0.131
6	43.9	27.5	62.7	0.202
7	43.4	9.20	21.2	0.673
8	43.5	5.40	12.4	0.906
9	43.6	2.98	6.83	1.165
10	43.7	1.82	4.16	1.380
11	43.8	1.06	2.42	1.616
12	43.8	0.78	1.76	1.754

	Exposure 4	−13.5°C		
1	44.8	44.3	98.9	0.004
2	44.7	43.1	96.5	0.015
3	44.6	40.0	89.8	0.046
4	44.4	35.2	79.3	0.100
5	44.2	30.6	69.3	0.159
6	44.1	25.2	57.2	0.242
7	43.8	8.63	19.7	0.705
8	43.6	5.00	11.45	0.941
9	43.4	2.90	6.68	1.175
10	43.2	1.80	4.16	1.380
11	43.0	1.18	2.75	1.560
12	42.8	0.90	2.10	1.677
	Exposure 5	−22.3°C		
1	45.0	44.0	97.8	0.009
2	44.9	42.2	94.0	0.026
3	44.8	39.2	87.5	0.057
4	44.8	34.5	77.0	0.113
5	44.7	29.8	66.7	0.175
6	44.7	25.0	55.9	0.252
7	44.0	8.24	18.7	0.728
8	↓	4.70	10.7	0.970
9		2.60	5.91	1.228
10		1.76	4.00	1.397
11		1.20	2.72	1.565
12		0.94	2.14	1.669
	Exposure 6	−29.0°C		
1	43.6	43.6	100.0	0.000
2	43.8	42.4	96.8	0.014
3	44.2	39.0	88.4	0.053
4	44.4	34.0	76.6	0.115
5	44.8	29.7	66.4	0.177
6	44.9	24.8	55.2	0.258
7	43.5	7.94	18.25	0.738
8	43.5	4.80	11.05	0.956
9	43.6	2.86	6.56	1.183
10	43.7	1.78	4.07	1.390
11	43.8	1.16	2.65	1.576
12	43.9	0.94	2.14	1.669

Exposure 7 −38.0°C

1	45.0	44.5	98.9	0.004
2		42.5	94.5	0.024
3		40.4	89.8	0.046
4		36.0	80.0	0.096
5		32.0	71.2	0.147
6		27.8	61.8	0.209
7		10.3	22.9	0.640
8		6.32	14.05	0.851
9		3.90	8.66	1.062
10		2.63	5.85	1.232
11		1.77	3.94	1.404
12	↓	1.18	2.62	1.581

Exposure 8 −46.5°C

1	43.0	43.0	100.0	0.000
2		40.5	94.2	0.025
3		37.0	86.0	0.065
4		34.0	79.0	0.102
5		30.0	69.8	0.156
6		25.0	58.1	0.235
7		9.03	20.9	0.679
8		5.57	13.2	0.879
9		3.30	7.68	1.114
10		2.16	5.03	1.298
11		1.33	3.10	1.509
12	↓	1.08	2.51	1.600

Exposure 9 −54.5°C

1	43.0	41.2	95.8	0.018
2		40.0	93.0	0.031
3		37.2	86.5	0.062
4		32.0	74.5	0.127
5		28.7	66.8	0.175
6	↓	23.4	54.4	0.264
7	42.8	8.72	20.4	0.690
8	42.8	5.33	12.45	0.905
9	42.7	3.10	7.26	1.139
10	42.6	2.02	4.74	1.324
11	42.5	1.35	3.18	1.497
12	42.4	1.08	2.55	1.593

103a-0 35mm Film   Blue Filter   15 Sec. Exposure

Step Number	% Trans. of Fog	Total Trans.	% Trans. Above Fog	Density Above Fog
		Exposure 1	16°C	
1	31.0	31.0	100.0	0.000
2	31.1	29.0	93.3	0.029
3	31.2	25.5	81.8	0.086
4	31.3	20.5	65.5	0.183
5	31.5	15.7	49.8	0.302
6	31.6	12.0	38.0	0.420
7	31.5	2.75	8.70	1.061
8	31.4	1.32	4.20	1.377
9	31.4	0.61	1.94	1.713
10	31.3	0.35	1.12	1.951
11	31.1	0.196	0.63	2.210
12	31.0	0.120	0.39	2.409
		Exposure 2	5.8°C	
1	31.8	31.0	97.5	0.010
2	31.8	29.5	92.8	0.032
3	31.7	27.5	86.8	0.061
4	31.6	22.5	71.2	0.147
5	31.5	18.2	57.8	0.238
6	31.4	14.5	46.2	0.335
7	31.2	3.70	11.9	0.924
8	31.2	1.85	5.93	1.226
9	31.0	0.78	2.52	1.598
10	31.0	0.39	1.26	1.899
11	30.9	0.16	0.52	2.283
12	30.8	0.12	0.39	2.408
		Exposure 3	-2.6°C	
1	31.4	30.5	97.2	0.012
2	31.5	29.5	93.6	0.028
3	31.6	26.0	82.3	0.084
4	31.6	21.5	67.0	0.173
5	31.7	18.2	57.4	0.241
6	31.7	14.5	45.8	0.339
7	31.5	3.70	11.7	0.931
8	↓	1.96	6.23	1.205
9		0.96	3.04	1.517
10		0.55	1.75	1.756
11		0.29	0.92	2.036
12		0.196	0.62	2.207

		Exposure 4	−11.6°C	
1	31.8	31.0	97.5	0.010
2	31.8	29.0	91.2	0.040
3	31.8	27.0	85.0	0.070
4	31.9	23.0	72.2	0.141
5	31.9	19.5	61.2	0.213
6	32.0	15.5	48.4	0.315
7	31.5	4.60	14.6	0.835
8	↓	2.45	7.78	1.109
9	↓	1.05	3.34	1.476
10	↓	0.55	1.75	1.756
11	↓	0.216	0.69	2.161
12	↓	0.118	0.37	2.420
		Exposure 5	−20.6°C	
1	31.0	30.5	98.5	0.006
2	↓	29.5	95.2	0.021
3	↓	27.5	88.7	0.052
4	↓	23.0	74.2	0.129
5	↓	20.0	64.5	0.190
6	↓	16.0	51.6	0.287
7	↓	5.30	17.1	0.767
8	↓	2.65	8.55	1.068
9	↓	1.20	3.87	1.412
10	↓	0.59	1.90	1.721
11	↓	0.216	0.70	2.154
12	↓	0.098	0.32	2.500
		Exposure 6	−31.0°C	
1	31.8	31.8	100.0	0.000
2	31.7	30.5	96.2	0.016
3	31.5	28.0	89.0	0.050
4	31.2	25.0	80.2	0.095
5	31.0	21.5	69.4	0.158
6	30.8	18.0	58.4	0.233
7	31.5	6.20	19.7	0.705
8	↓	3.20	10.2	0.993
9	↓	1.50	4.76	1.322
10	↓	0.73	2.32	1.634
11	↓	0.26	0.83	2.083
12	↓	0.14	0.44	2.350

Exposure 7 -38.0°C

1	30.0	30.0	100.0	0.000
2	↓	29.0	96.6	0.015
3	↓	26.5	88.4	0.053
4	↓	23.0	76.6	0.115
5	↓	20.5	68.4	0.164
6	↓	17.0	56.6	0.247
7	29.5	5.90	20.0	0.698
8	29.6	3.14	10.6	0.974
9	29.8	1.41	4.73	1.325
10	30.0	0.667	2.22	1.653
11	30.2	0.274	0.91	2.040
12	30.4	0.137	0.45	2.346

Exposure 8 -44.5°C

1	31.6	31.0	98.1	0.008
2	31.4	30.0	95.5	0.019
3	31.2	28.3	87.6	0.057
4	31.0	25.0	80.7	0.093
5	30.8	22.0	71.4	0.146
6	30.6	18.5	60.5	0.218
7	30.0	7.20	24.0	0.619
8	↓	3.90	13.0	0.886
9	↓	1.86	6.20	1.207
10	↓	0.88	2.93	1.533
11	↓	0.37	1.23	1.910
12	↓	0.20	0.67	2.176

Exposure 9 -48.0°C

1	31.0	31.0	100.0	0.000
2	↓	30.0	97.6	0.014
3	↓	28.5	92.0	0.036
4	↓	25.5	82.3	0.084
5	↓	22.0	71.0	0.148
6	↓	19.0	61.3	0.212
7	↓	7.45	24.0	0.619
8	30.9	4.10	13.3	0.876
9	30.8	2.06	6.68	1.175
10	30.6	1.08	3.53	1.452
11	30.5	0.51	1.67	1.777
12	30.4	0.372	1.22	1.913

Exposure 10 -56.5°C

1	31.0	31.0	100.0	0.000
2	↓	30.5	98.4	0.007
3		30.0	96.7	0.014
4		27.0	87.1	0.059
5		25.0	80.6	0.093
6		21.0	67.7	0.169
7		9.00	29.0	0.537
8		5.70	18.4	0.735
9		3.04	9.80	1.008
10		1.67	5.39	1.268
11		0.804	2.59	1.586
12		0.550	1.77	1.752

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