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JULY 16, 1945 NUCLEAR EXPLOSION:

PRELIMINARY REPORT ON THE SPECTRUM AND RADIATION

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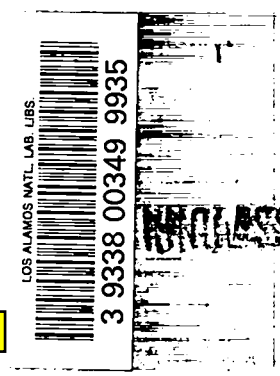

Weapon Data
(Effects and Instrument)

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Part I--Photometry

Abstract

Two spectrograms were obtained of the nuclear explosion. A high time resolution spectrogram covering the first 5.5ms taken with a drum spectrograph, was secured from station 10^4 North. A low time resolution spectrogram covering the first 1.5 sec, taken with a modified Bausch and Lomb Littrow small quartz spectrograph was secured from the same station.

From the two records lines and bands have been partially identified. All lines and bands have been listed.

Approximate temperatures are obtained from the Hilger spectrogram for the first 5ms.

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Introduction

A Hilger Intermediate Quartz Spectrograph as well as a Bausch and Lomb Littrow Spectrograph were rebuilt to take a spectrum of the bomb as a function of time. It was the purpose of the Hilger Spectrograph to get a short time, high time resolution record of the bomb for the first 10 ms. The Bausch and Lomb spectrograph, equipped to take a roll of 7" Aero film fifteen feet long, was intended to record the spectrum of the explosion as well as the rising ball of fire for about 1000 seconds, with low time resolution.

The spectra obtained from these two instruments* were to give the temperature of the nuclear explosion as a function of time.

Apparatus

Hilger High Speed Spectrograph (See Fig. 1 for schematic drawing and Figs. 3-7 for photographs).

The plate holder assembly of the spectrograph was removed and replaced by a hollow aluminum cylinder. (See Figs. 5-7 for photographs). The film was attached to the inside of this drum, which was rigidly keyed to a synchronous motor. The film had a linear velocity of about 60 meters per second. The exact rate was obtained from marks produced by timing lights controlled by a 1000 cycle tuning fork oscillator. Since it was impossible to focus the spectrograph visually, and very tedious to adjust it photographically, a gage was designed which gave the exact distance between a finished surface on the spectrograph and the undersurface of the drum. Minor adjustments were effected by moving the slit. A special spring controlled shutter (See Fig. 4 for photograph and Fig. 1 for schematic drawing) was mounted directly in front of the slit (in fact it took the place of the Hartman diaphragm), and limited the exposure time to approximately ten milliseconds. The shutter was tripped 17 ms in advance of the detonation by a remote control mechanism.

The delay of the shutter and its exposure time were checked with a phototube amplifier connected to a single sweep scope.

The spectrum of an H-4 Mercury Vapor lamp was used as a wave length standard. This spectrum was photographed two times, about 180° apart on the drum, to assure at least one measurable record in case the other one should have the spectrum of the bomb superimposed on it.

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* An almost identical set of instruments was located at 10^4 West. The B and L Spectrograph was not set up in time for the explosion, the other, a large Hilger Spectrograph failed to operate.

The time resolution of the spectrograph is obviously a variable. It depends on the slit length or the size of the image on the slit. The time resolution is constant only if the slit length equals the size of the image, for image sizes smaller than the slit length, the time resolution is governed by the size of the image. The time resolution may easily be computed from

$$T = 16.95 L \mu s \quad 1)$$

where L is the length of the slit or image size in mm.

Thus for times less than one tenth of one millisecond the time resolution was certainly better than 9μs, for times of the order of ten microseconds the resolution was probably less than five μs, and at the end of five milliseconds was probably about 0.08 milliseconds [2].

Bausch and Lomb Small Littrow Spectrograph (See Fig. 8). To cover the tremendous change in illumination which would take place in the first ten seconds during which the spectrograph was to record the spectrum, an extremely complicated varying speed drive was designed. A hydraulic motor drove the film take up spool at a speed which was approximately directly proportional to the illumination. In other words if the illumination decreased by a factor of two, the linear speed would also drop by a factor of two. A special cam was designed which would regulate the motor speed in accordance with the theoretically predicted brightness curve.

The speed ratio between maximum and minimum speed was 40,000 to 1.[3] The film started with a speed of about 400 cm/sec and then followed approximately a 1/t law (t, time in seconds). A 16mm Cine Kodak movie camera, mounted in front and slightly to one side of the spectrograph took a picture of the slit while the spectrograph was recording the explosion. This film showed that at no time was the image of the bomb on the slit, but the spectrograph was aimed at a point on the ground apparently several hundred yards in front of the tower. The light reflected off the ground was enough to blacken the film at the beginning of the spectrogram to a density of about 2 despite an exposure of about 1/100 sec. The film is interpretable to 1.5 seconds after which the hydraulic mechanism seems to have stalled, resulting in an overall fogging of the film after 1.5 secs.

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1) Actually the linear velocity of the film was 59.0 meters per second, hence the constant 16.95 rather than 16.67.

2) These figures are based upon the size of the ball of fire as a function of time (J.E. Mack, LA-531).

3) The hydraulic system was designed by N. Bifano.

Installation

The high speed drum spectrograph was located in a concrete bunker 10,000 yards, (Station 10^4 North), from the tower on which the bomb was detonated. The instrument was lined up by focussing a searchlight, mounted 25 feet below the bomb, on the slit. The condensing lens was a quartz fluorite achromat of 30 cm focal length.

The Bausch and Lomb low time resolution spectrograph was mounted on a Martin gun turret. The gun turret was installed on the roof of the same 10,000 yard bunker. An operator was to aim the spectrograph at the center of the slowly rising ball of fire.

Exposure

In both spectrographs Eastman Kodak Tri-X Aero film was used, mainly because of its low shrink base. No other film was available except Super XX, which although slightly slower would have given trouble with excessive shrinkage.

The slit width and length of the High Speed Spectrograph were 100μ and 5mm respectively. This rather wide slit width was chosen to make sure that the very first stages would be recorded by the instrument. The spectrograph was used at its full aperture of f:12.5.

The Bausch and Lomb Littrow Spectrograph had a slit width of 20μ and length of 4mm, and an aperture of f:13.6.

Discussion of Spectrogram Obtained With High Speed Spectrograph

(See Figs. 10-17 for photographs).

A record of the explosion was obtained for the first 5.5ms and showed that no light of wave lengths shorter than 2990 Å was recorded on the film of the spectrograph.

The spectrum is similar to that of the sun in at least two respects, it is continuous, and a great number of absorption bands may be seen, especially in the near ultra-violet region.

Although the spectrum does not change with time for the first 5.5 to 6ms, except for temperature, the very beginning of the spectrum shows some extremely interesting features (See Figs. 11-15 for photographs).

At the beginning, about one to ten microseconds before

any radiation from the shock front reached the spectrograph, a flash of light lit up the air surrounding the bomb, apparently forming a luminous sphere around the gadget of 60 to 90 meters in diameter. The luminosity of this "sphere" did not last longer than five microseconds, however, it is difficult to determine how short it was. The radiation from this luminous sphere produced an emission spectrum of eleven lines. See Table V and Fig. 15 for photograph of emission lines.

A few experiments have been carried out in an attempt to reproduce this spectrum in the laboratory, however, a more detailed account of the results is given below.

The temperature radiation behaved quite peculiarly for the first 70 microseconds. The temperature stayed constant (within the accuracy of measurement) from zero to 38 microseconds, then increased within five microseconds by 60% and stayed at this temperature from 38 to 70 microseconds. There is indication of a third such period, but it is not very pronounced and it may very well be due to a stain in the negative. After this period of violent change, the bomb reached its highest temperature at 200± 50 microseconds, and then gradually cooled to a temperature of 5000° K after 5.1 milliseconds. (The highest temperature is not known for reasons which will be explained below, but it may be inferred from the densities of the film where the highest temperature was reached).

Table I gives the temperature as a function of time from 0.8 to 5.6 milliseconds. This table should be compared with Table II which shows temperatures computed by J. L. Magee[1] on the basis of Brian O'Brien's Crossroads results.[2]

The spectrogram obtained with the Bausch and Lomb Spectrograph was not used for temperature determination.

Analysis of Film

The method used in determining the temperature of the exploding bomb was suggested by Dr. S. N. Nicholson of Mt. Wilson observatory, and almost all the important phases of this work were directed by him.

The nature of the apparatus made it practically impossible to put a stepwedge or even the spectrum of a standard source on the film, we were therefore compelled to find the ratio of energies at two wave lengths from the film and compare them with theoretically

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1) J. L. Magee, Crossroads Report

2) Brian O'Brien, Gordon Milne, Brian O'Brien, Jr., Crossroads Technical Report, Test A, Project No, II-12.

calculated values for different temperatures. A Planckian distribution was assumed.

Density measurements were made at 3470 A and 5700 A, although a greater spread between the wave lengths would have been desirable. It was felt, however, that 3470 A was the shortest possible wave length that could be used and still not be affected by absorption.

Two stepwedges were prepared, one for each wave length, covering the necessary densities. The wedges were printed on film of the same emulsion number used for the spectroscopic record. Wratten filters introduced between the light source and the film gave the desired wave lengths, except for the shortwave length filter which transmitted light of about 4000 A rather than 3470 A.

The position of one characteristic curve with respect to the other was obtained by using a graph prepared by the Eastman Kodak Company, showing the sensitivity (reciprocal of exposure in ergs/cm^2 required to produce a density of 1.0) as a function of λ. The ratio of energies for blue and yellow light to produce the same density was easily obtained from this curve. Fig. 2 shows schematically the two characteristic curves for 4000 and 5700 A, and their position relative to each other. The log It difference at D 1.0 corresponds to the above mentioned ratio. All density measurements were made on a Capstaff - Purdy type densitometer.

The theoretically computed ratio of energies for the two wave lengths was corrected for the dispersion of the spectrograph, and the logarithm of this value was plotted against corresponding temperatures. The temperature of the exploding bomb was found by transferring the log It difference from the characteristic curves to the plot T vs. log It_{5700}/ It_{4000} and reading off the temperature.

Discussion of Results

There are some serious and justified objections which may be raised against the method of analysis.

The matter of reciprocity law failure cannot be taken lightly, because of the tremendous range in exposure time between the laboratory produced stepwedges and the actual spectrogram. The ratio of exposure times is approximately 2.10^6 to 1.

Little seems to be known about reciprocity law failure for very high intensities and extremely short times, and although some curves[1] were available to us showing reciprocity law failure for densities up to 2.0 and time of 10^{-6} seconds, and a light source of 3000° K, they were of little value to us for quantative work.

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1) Supplied by Eastman Kodak Company

The probable effect of reciprocity law failure on the H and D curves is shown schematically in Fig. 9. This figure shows the characteristic curves used for the temperature determination, and the assumed actual H and D curves. These curves show that for the same density difference, (density at 4000 A minus density at 5700 A) the actual difference in the logarithm of illumination, $\Delta \log E_2$, is greater than the measured difference, $\Delta \log E_1$. $\Delta \log E_1$ then represents the quantity used in determining the temperature from the curve T vs $\log I_{5700}/I_{4000}$. $\Delta \log E_2$ being greater than $\Delta \log E_1$, gives a lower temperature. One would therefore suspect that the temperatures presented in this report are too high. Magee's results show exactly the opposite.

A series of H and D curves were derived from the above mentioned Eastman Kodak Company reciprocity law failure curves, covering times from 100 to 10^{-5} seconds. If one computes the gamma from these curves for 100 seconds, which would correspond to the exposure time for the stepwedges, and 10^{-5} sec, one gets a ratio of about 1.6 between the two gammas. This would indicate an error of approximately 15% at 6000°, 25% at 10,000° and 6% at 20,000°. The error is much greater, however, if the fairly flat top of the H and D curve is used, as it was in this experiment.

The maximum densities measured on the Hilger Spectrogram exceed maximum densities obtained in the laboratory by 0.1 units for the blue and about 0.05 for the yellow. This phenomenon has not been adequately explained.

One may check the consistency of the results by comparing temperatures and densities in Table I. Thus for example a temperature of 5.10^3 °K at 5ms seems to give a lower density at 3470 Å and 5700Å than a temperature of 4.8×10^3 °K at 1.72ms. Of course, these variations are well within the error of 15% given above.

An error which is hard to evaluate but which none the less may be very serious may have been introduced by assuming the validity of the data obtained from the Eastman Kodak Company sensitivity curve.

It is difficult to believe that there is such a tremendous discrepancy between our results and O'Brien's measurements. However, O'Brien's brightness determination is certainly far superior in many respects.

Part II--Spectroscopy

Although temperature determination was of primary importance, the spectrum in itself showed interesting enough features to make a detailed investigation extremely worth while. Any information concerning the identification and determination of absorption bands and lines might shed some more light on the temperature of the explosion and the physics of explosion in general.

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General Discussion of Spectrum

The spectrogram obtained with the Hilger Intermediate Quartz Spectrograph shows a great many absorption lines and bands, whose intensity, broadness, and structure do not change appreciably if at all for the first 5.5 milliseconds. The only exceptions are three absorption bands at 3067, 3093, and 3100 Å, which gradually fade away and disappear at the end of 5.5 milliseconds. The emission lines mentioned earlier in the report will be discussed below. It is interesting to note that the Bausch and Lomb spectrogram does not show these lines, which may probably be explained by the misalignment of the spectrograph (it was focussed on a point on the ground a considerable distance in front of the bomb). Significant changes occur in the spectrum after six milliseconds, as evidenced by the Bausch and Lomb record. A great number of new bands and lines appear, lines or bands which had a broad and diffuse appearance are sharper and show considerable structure. A wave lengths chart has been prepared for both records, showing the position of the lines, their intensities (also approximately indicated by the width of the line) and wave lengths. This chart represents the actual appearance of the lines on the film, the lines are not shown on a linear wave length scale, but conform to the dispersion of the spectrograph. All intensities are listed on a scale of 10. See Figs. 18-22 for wave length charts. No intensities are given for about half of the lines found on the Hilger record. These lines could only be measured after having been printed in high contrast. A great number of prints were necessary to bring out all lines in about 2 centimeters length of spectrum. It is therefore believed that intensities derived from these records are of no great value. The measurement of wave lengths on the Bausch and Lomb film presented great difficulties, because the dispersion changed continuously. The plate holder was not well enough designed to hold the film in the focal plane for the whole length of the run. However, by using lines measured on the Hilger record as secondary standards on the Bausch and Lomb record fair results have been obtained. In some instances where the Bausch and Lomb measurements showed a constant deviation in wave length from similar measurements on the Hilger record, the Bausch and Lomb wave lengths could easily be corrected by direct comparison.

Table III is an attempt at recording the changes which take place in the structure and appearance of the bands in the first 1.5 secs. Approximate times are given for the appearance and disappearance of almost all bands and lines. No great weight can be attached to these times since the exact point of disappearance or appearance is a matter of personal opinion, and the error in the time scale itself is of the order of 20 to 30%.

The fourth column in the aforementioned table aims to indicate changes in structure or character of the lines and bands. Thus for example, the line at 3840 Å which is easily recognizable on the Hilger record as a very broad and diffuse absorption line, is very difficult to find on the Bausch and Lomb spectrogram, but closer study reveals that the single line at 3840 Å corresponds to the lines num-

[redacted]

bered 54 to 58 inclusive. These lines merge into one diffuse line at 6 milliseconds. Again at 3237 Å on the Hilger record there appears one line, the same line may be seen on the Bausch and Lomb spectrogram (See lines numbered 9 and 10), but 6 milliseconds after t_o the line has split into two.

Accuracy of Measurement

A table of limits of errors and wave lengths has been prepared for both spectrographic records. See Tables IV, V, and VI. These errors have been estimated from the uncertainty in the comparator measurements, and the uncertainty in the dispersion formulae. The Bausch and Lomb spectrogram offers additional difficulties due to the irregular film motion and the failure of the film holder to keep the film in one plane. See Fig. 23 for photograph. Limits of error have been estimated for wave lengths from 610-375 mμ by taking into account the uncertainty due to the erratic behavior of the film. Errors for wavelengths less than 375 mμ may be estimated by direct comparison with the Hilger wave length chart. It will be noted that all wave lengths of the Bausch and Lomb record from 3840Å - 3067Å are low by about 10Å when matched against the same lines of the Hilger record. This is primarily due to the erratic dispersion of the low time resolution spectrograph. Although the Bausch and Lomb wave lengths have been recorded on the wave length chart as computed, the above mentioned discrepancy of 10A has been made use of in Table VII by increasing each Bausch and Lomb wave length by 10Å. This was done to bring the latter in agreement with Hilger measurements.

Analysis of Spectrum

A great deal of time and effort has been spent on the identification of the lines and bands, and a few have been identified.

Dr. E. Teller suggested that the ultra-violet cut-off at 2990A was due to the formation of Ozone. The ultra-violet cut-off is shown as a function of time in Figs. 24 and 25. And indeed absorption bands extending from 3000 A to 3300 A check fairly well with wave lengths of published O_3 bands. Table VII gives a comparison between published data and wave lengths obtained in this experiment. The Bausch and Lomb readings have been corrected by adding 10 A, since the latter showed an almost constant deviation from corresponding Hilger measurements. The absorption lines whose origin seems to be fairly well established are the Calcium and Sodium lines at 420 millimicrons and 584 millimicrons respectively, believed to be CaI 42267A and NaI 5889.9, 5895.9 A. They are probably due to the dust and sand vaporized by the heat of the bomb. There is no evidence of these lines being present before 5 milliseconds.

The strong absorption lines at 3427, 3555, 3696, and 3840 A have aroused a great deal of interest and their striking resemblance to absorption lines occurring in mixtures of NO, NO_2, and H_2O has led to the belief that NO_2 was formed during the explosion[1].

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1) J. E. Mack, Space Time Report, LA -631

The formation of NO_2 has been discussed by J. Hirschfelder and J. L. Magee[1]. Melvin and Mulf[2] obtained a series of absorption bands with a NO - NO_2 - H_2O medium which bear a striking resemblance to the bands at 3427, 3555, 3696, and 3840A. Newitt and Outridge[3] obtain similar bands from the explosion of a CO - H_2O - NO medium at high pressures. They suggest that these bands may be due to the enhancement of certain bands of the normal NO_2 absorption spectrum. Table VIII is a comparison of wave lengths obtained by Melvin and Mulf, Newitt and Outridge, and wave lengths of bands obtained with the high speed spectrograph. The agreement is fairly good, the intensities seem to check with the published data.

The emission lines (See wave length chart and Table V) have been investigated by Dr. J. E. Mack. A picture was taken of the "glory hole" at Omega with a fast f 2 glass spectrograph. No visible radiation emanated from the hole. A ten hour exposure at a boiler rate of 6.5 KV resulted in two or three faint lines at approximately 4065, 4280, and 4348 A. These values may be compared with the emission lines of Table V. Further experiments will be necessary to substantiate these results. J. L. Magee suggested that the emission lines may be due to O^{II}.

---

1) J. Magee, J. Hirschfelder, LA-1020, Vol. VII, Chap. 4, Radiation Phenomena in Air Blast of Gadget

2) E. Melvin, O. Mulf, J.C.P. 3, 755, 35

3) Newitt, Outridge, J.C.P. 6, 752, 38

[redacted]

Part III--Figures and Tables

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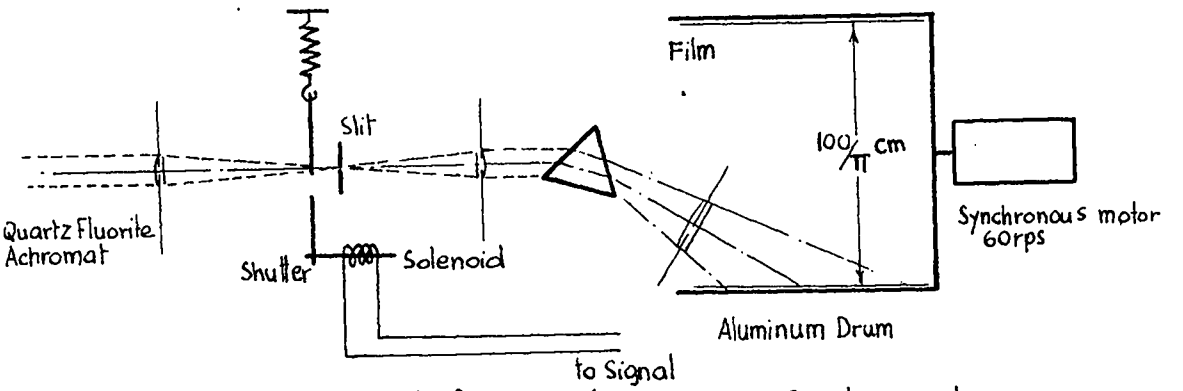

Schematic Drawing of E486 Drum Spectrograph
Fig. 1

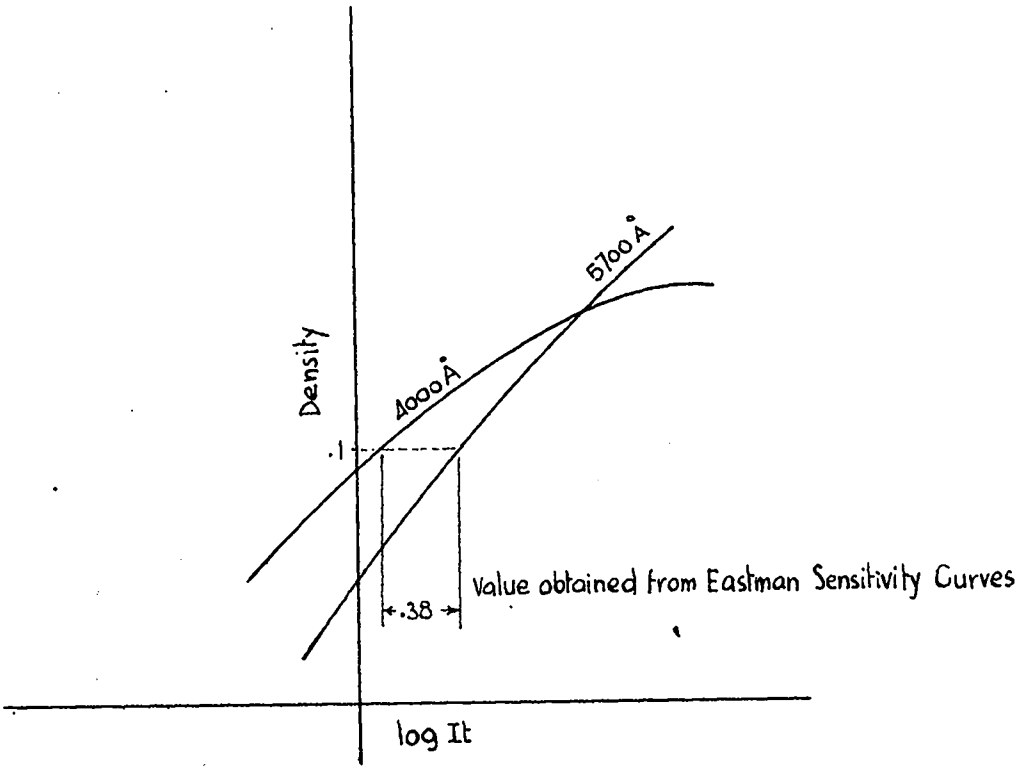

Fig. 2

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Figure 3

Hilger E 486 Quartz Spectrograph, showing the changing bag, shutter, and pip light connection. The changing bag made a light tight connection between the drum housing and the spectrograph itself. It also allowed daylight loading of the drum.

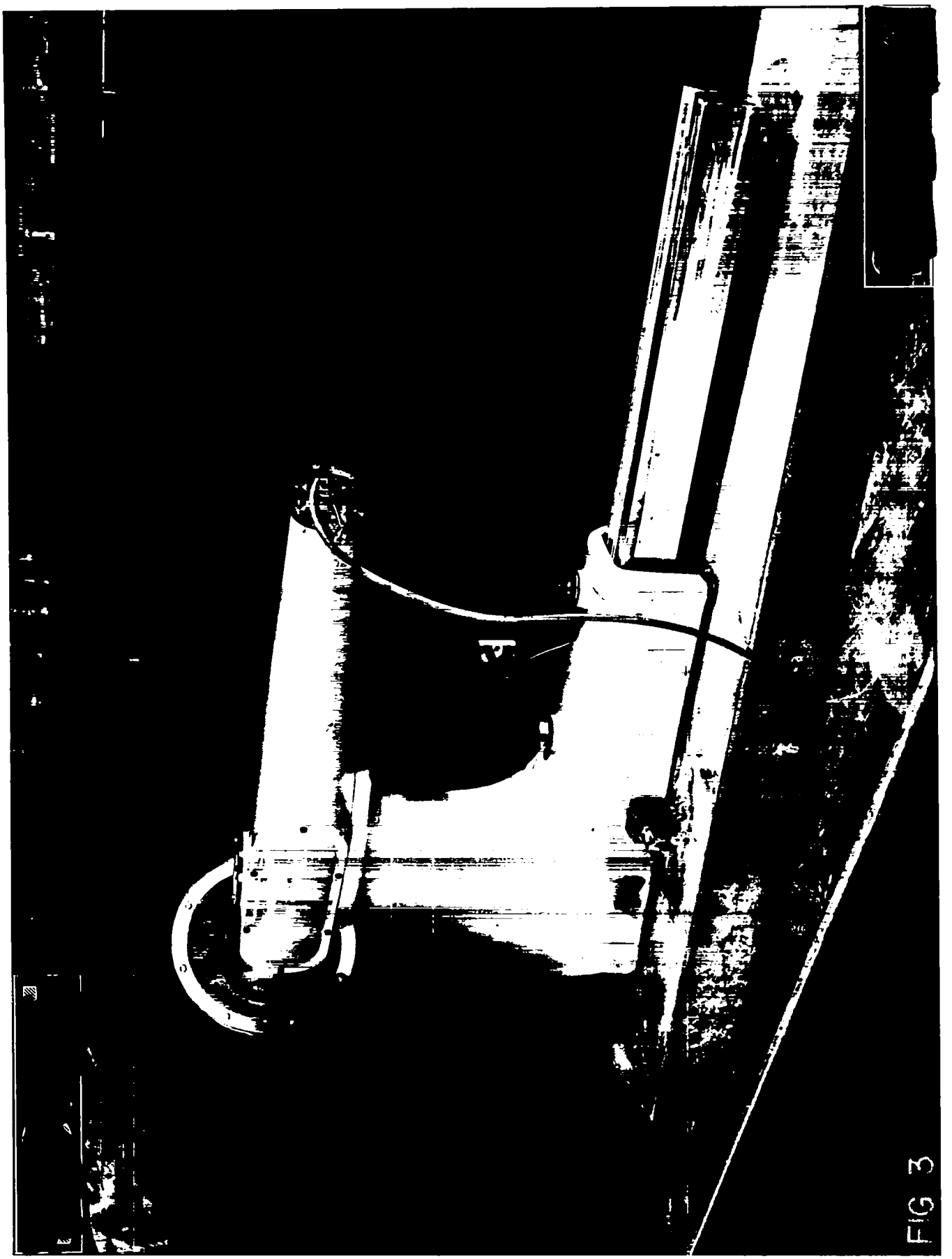


FIG 3

Figure 4

E 486 Hilger Spectrograph. Frontview of shutter and slit. The shutter slide is pulled across the slit by means of a spring. The shutter is released by a solenoid. The pip lights are operated automatically by the motion of the shutter. As the shutter moves past the slit a contact is established which closes a circuit to the piplights. The piplights are on as long as the slit is exposed to the lightsource.

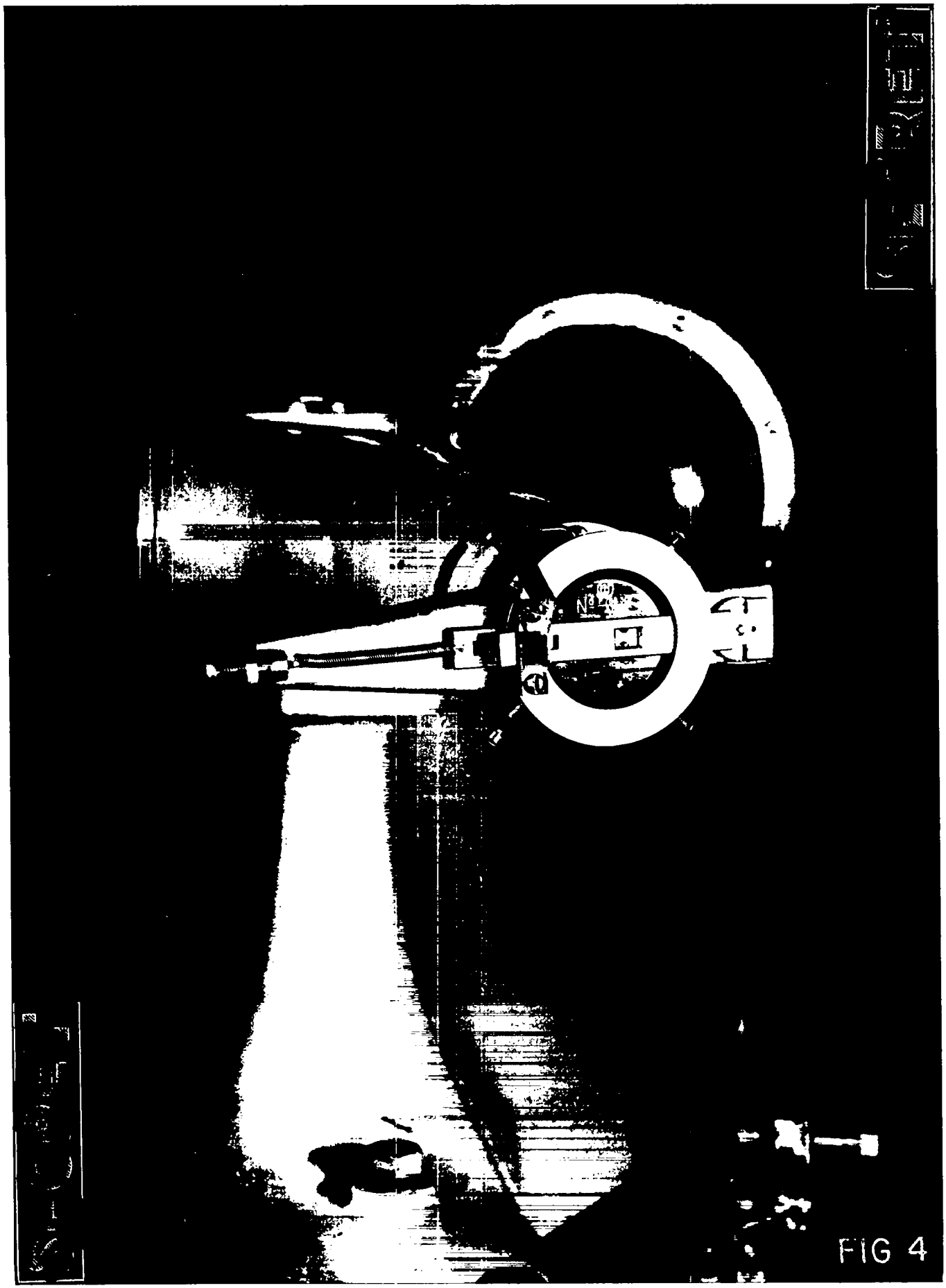


FIG 4

Figure 5

E 486 Hilger Spectrograph. Drum and drum housing. The grooves which guide the film in the drum are easily recognizable.

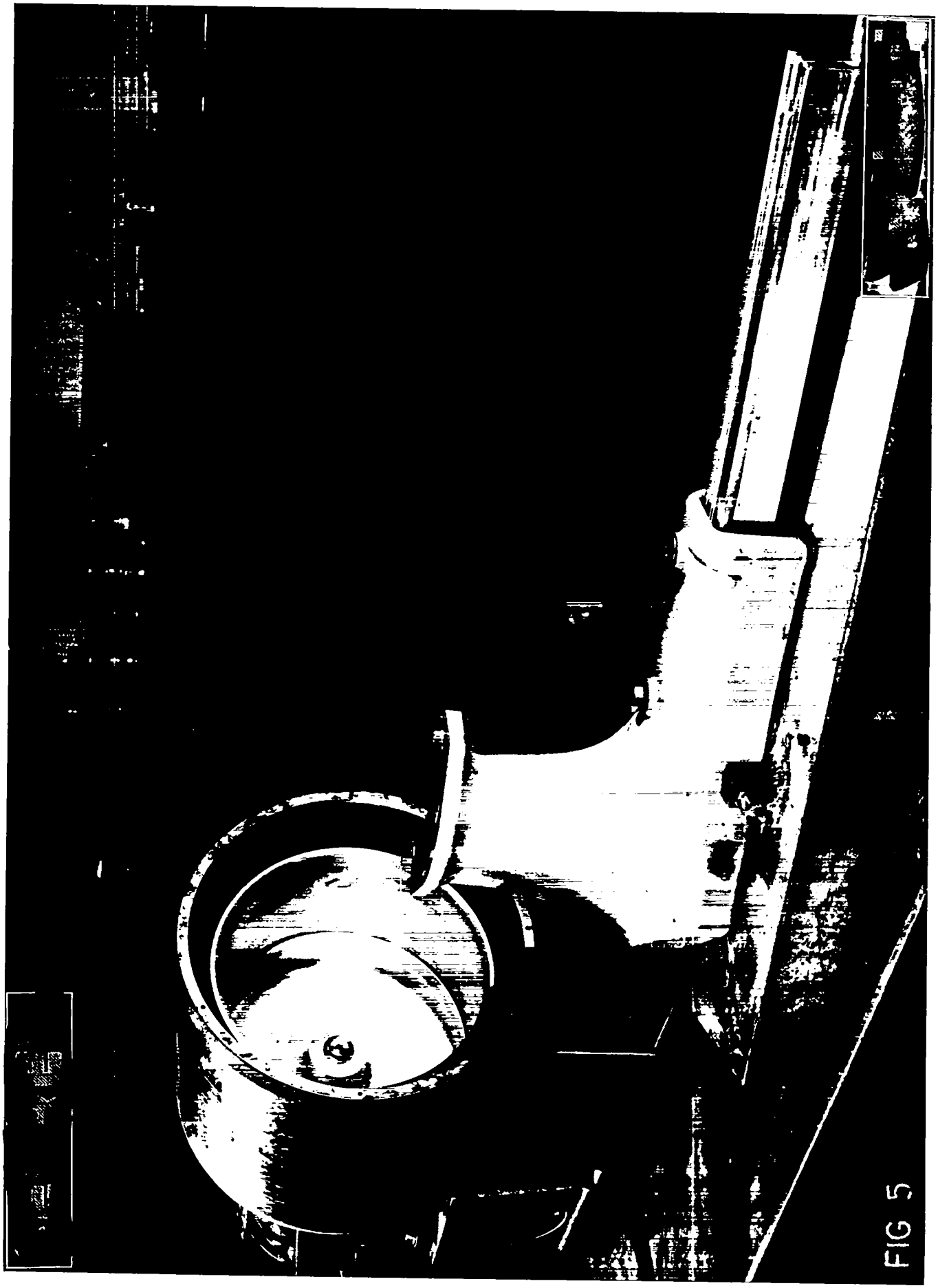


FIG 5

Figure 6

Hilger E 486 Spectrograph. The changing bag has been partly removed, showing the drum, and the business end of the spectrograph with its plate holder removed.

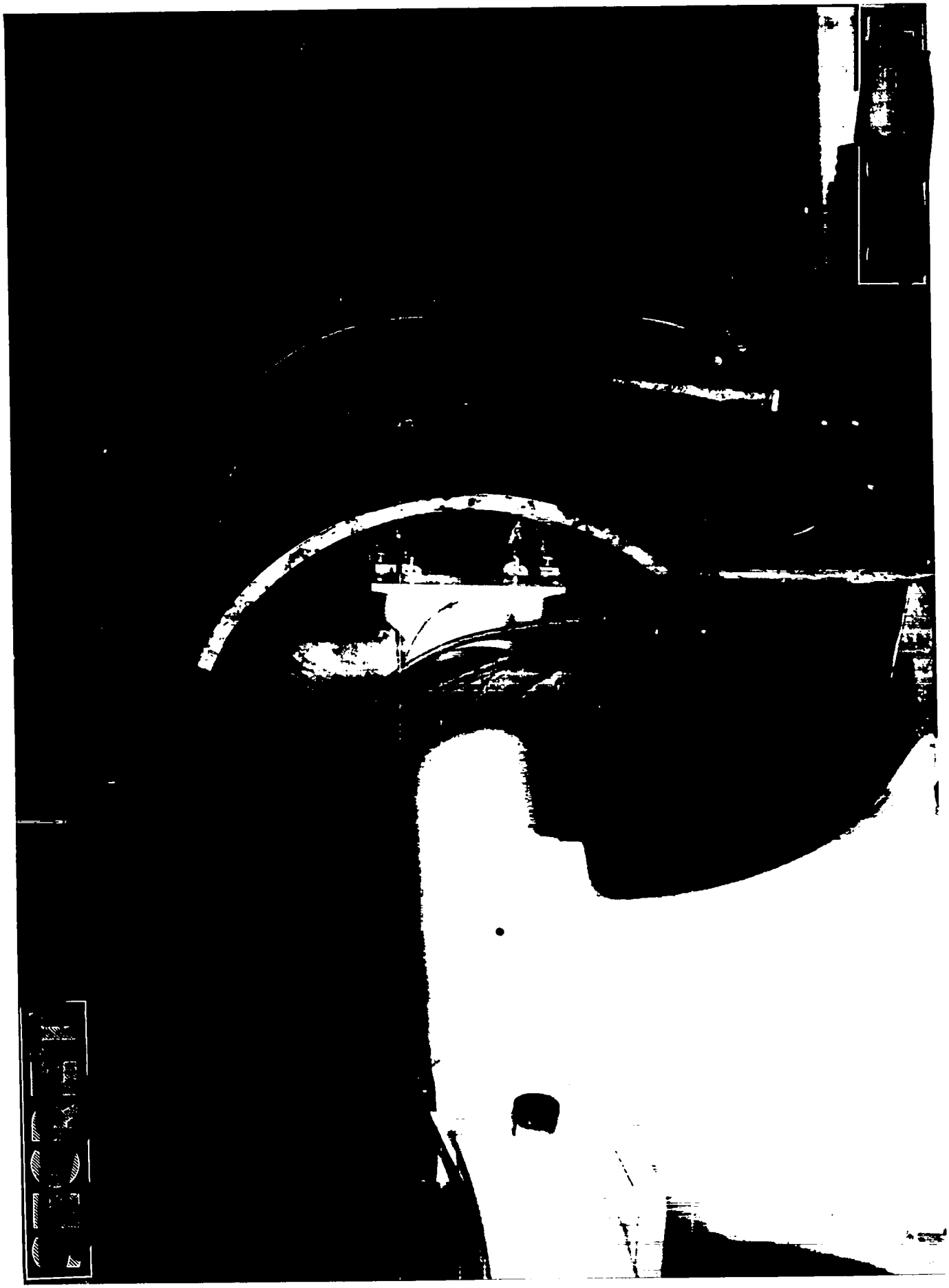
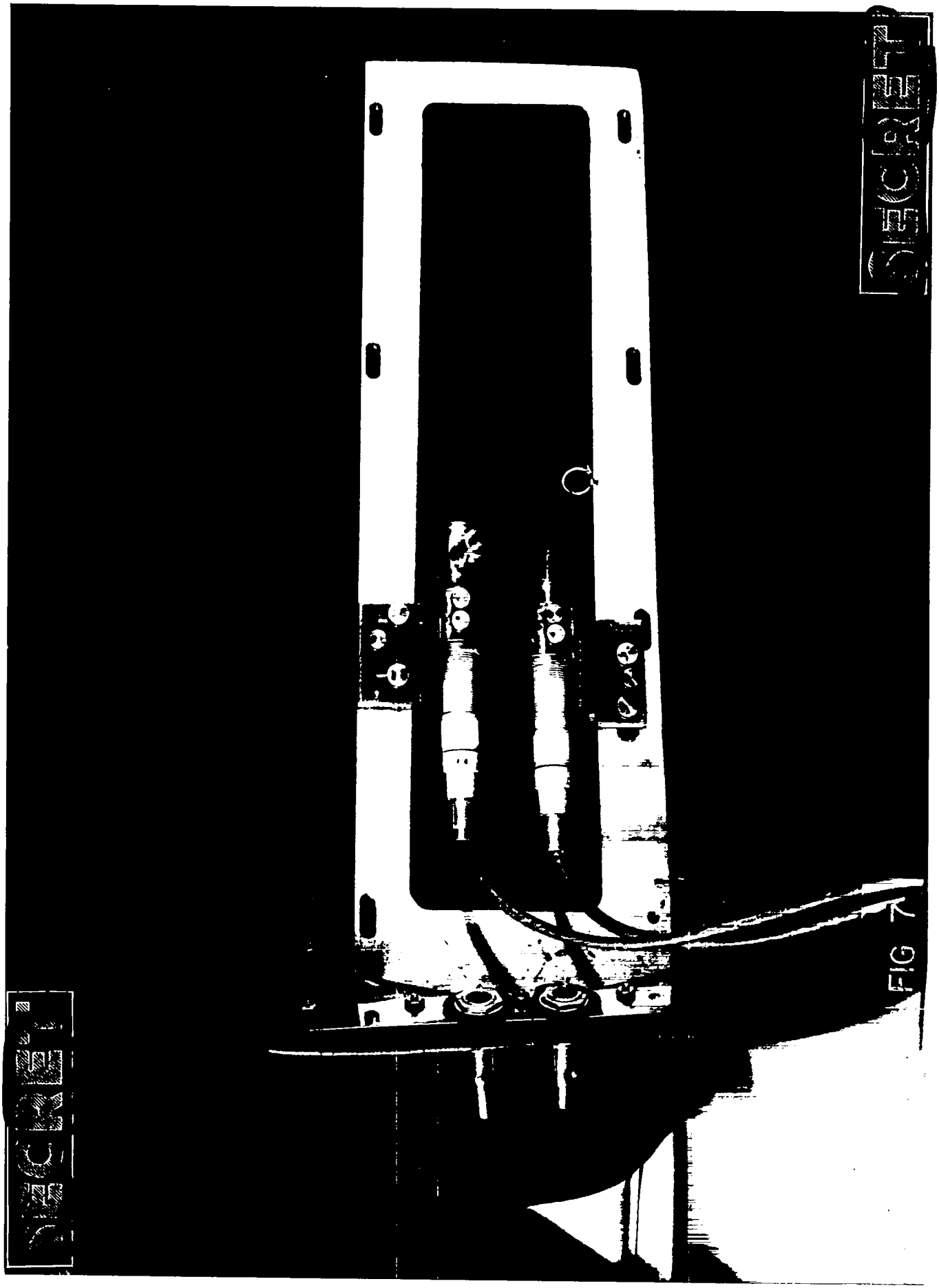
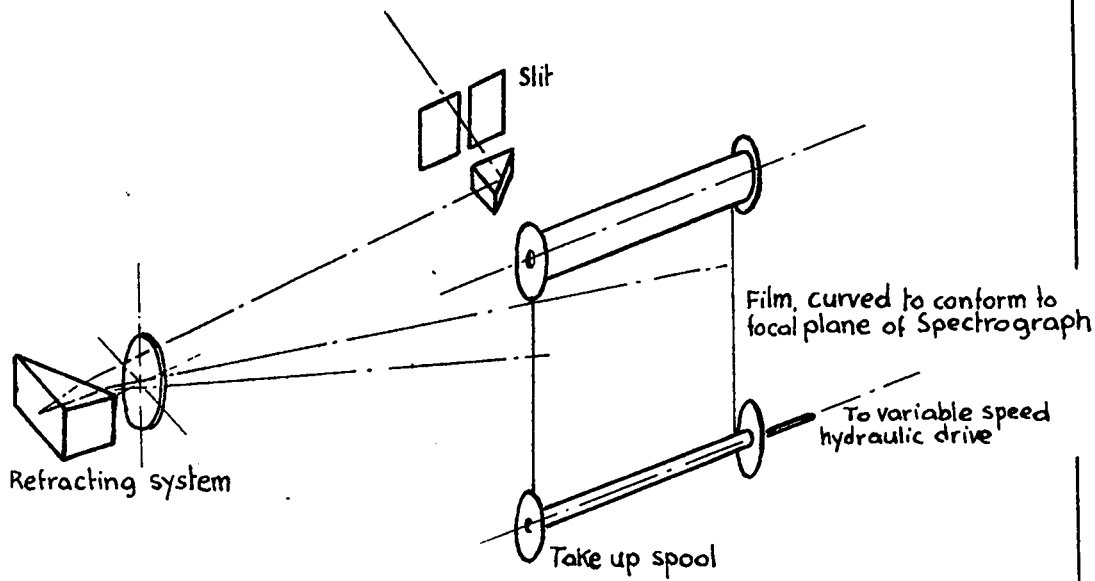


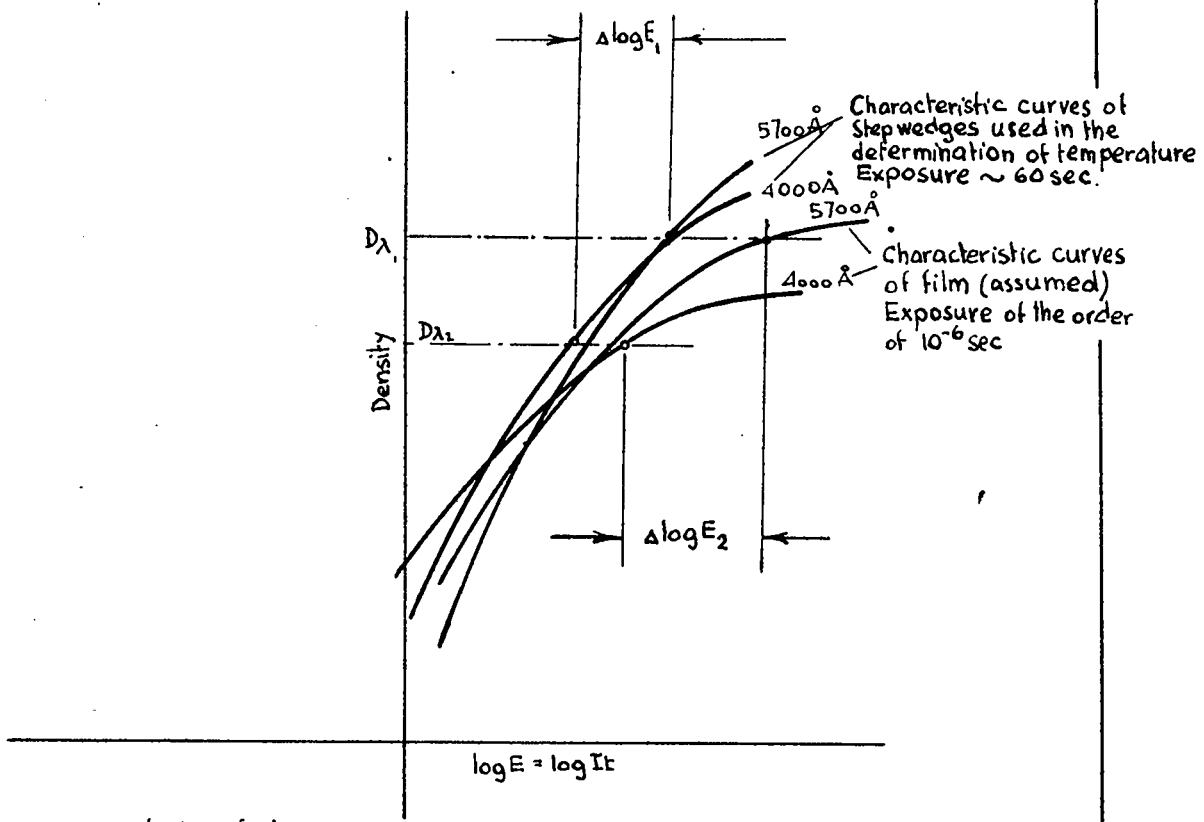
Figure 7

Hilger E 498 Quartz Spectrograph. This instrument failed to operate. This shows the piplight installation, which was similar on both instruments. The image of a neon bulb electrode was focussed on the film.





Bausch and Lomb modified small quartz Littrow Spectrograph
Fig. 8



Reciprocity law failure and its assumed effect on $\Delta \log E$ and Temperature
Fig. 9

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Figure 10

The Spectrum of the Bomb. Timescale, 1 millisecond corresponds to 59 mm. This record shows the spectrum for the first 3.8 ms. This spectrogram was taken with the E 486 Hilger Quartz Spectrograph. The violet end of the spectrum is on the left hand side of the figure, zero time is at the top.

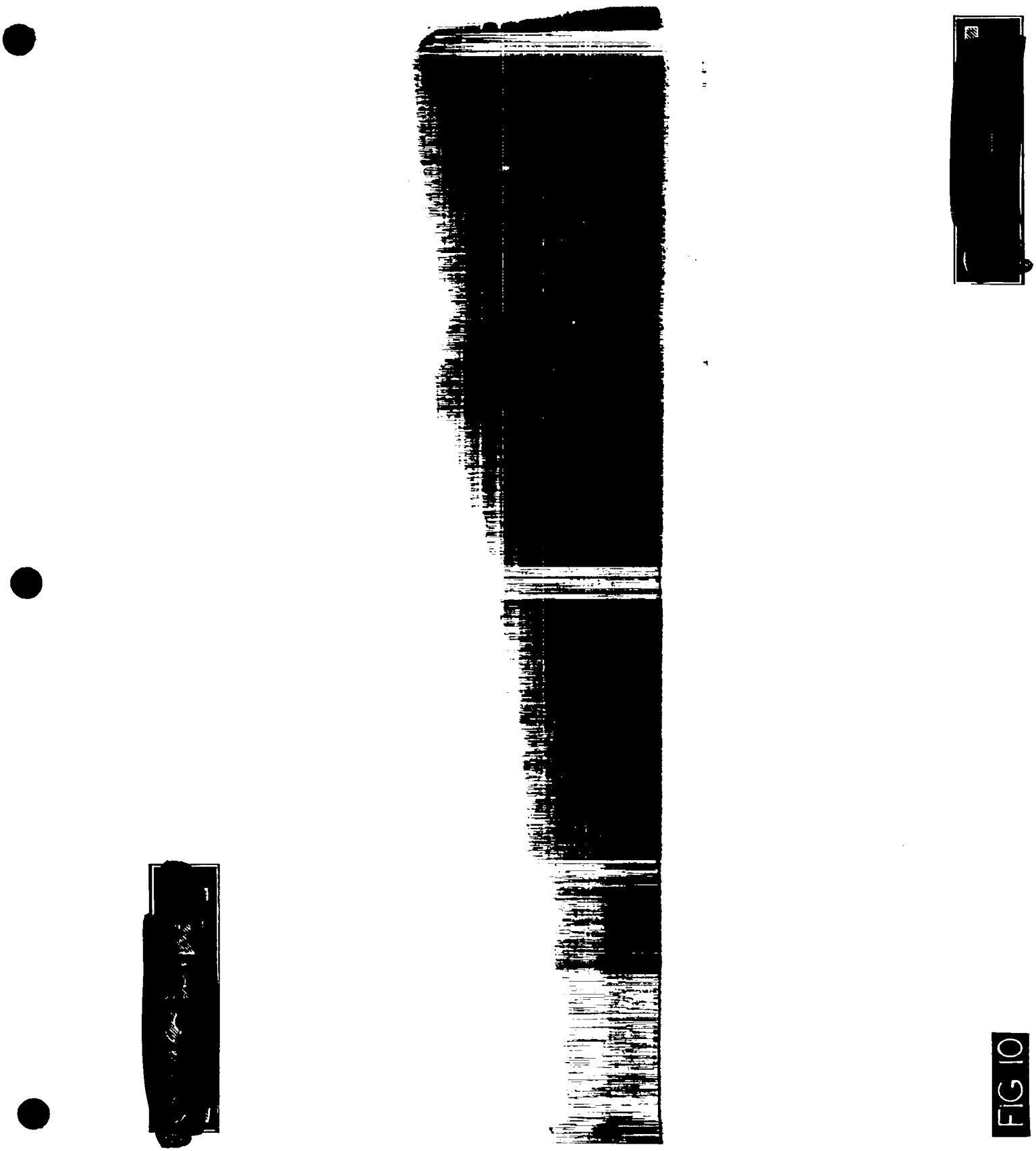

FIG 10

Figure 11

Bomb spectrum, 0-3.8 ms. Hilger E 486 quartz spectrograph.

FIG 11

Figure 12

Bomb spectrum, 0-3.8 ms. Hilger E 486 quartz spectrograph.

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FIG 12

[redacted]

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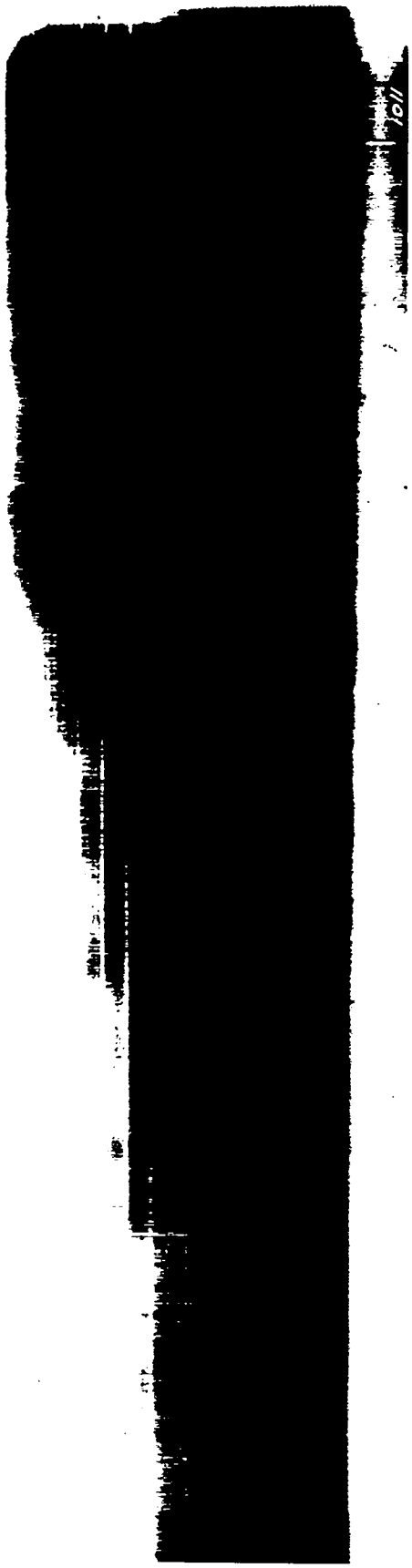
Figure 13

Bomb spectrum, 0-3.8 ms. Hilger E 486 quartz spectrograph.



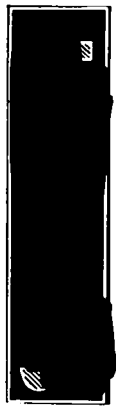


FIG 13

Figure 14

Bomb spectrum, 0-3.8 ms. Hilger E 486 quartz spectrograph.

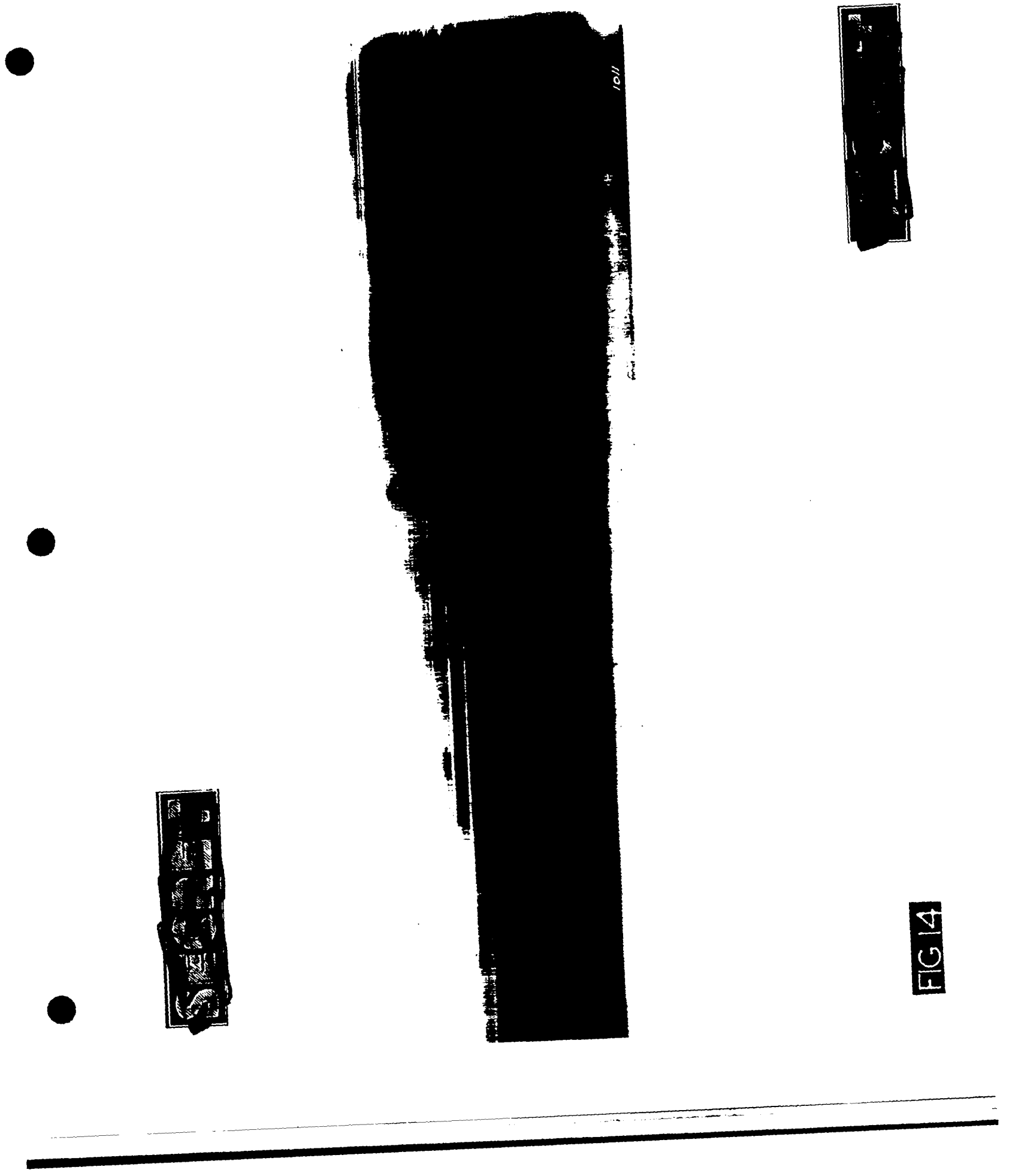


Figure 15

Bomb spectrum, 0-3.8 ms. Hilger E 486 quartz spectrograph. This print shows clearly the emission lines at the very beginning of the record.

FIG 15

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Figure 16

Bomb spectrum, 0-3.8 ms. Hilger E 486 quartz spectrograph.

FIG 16

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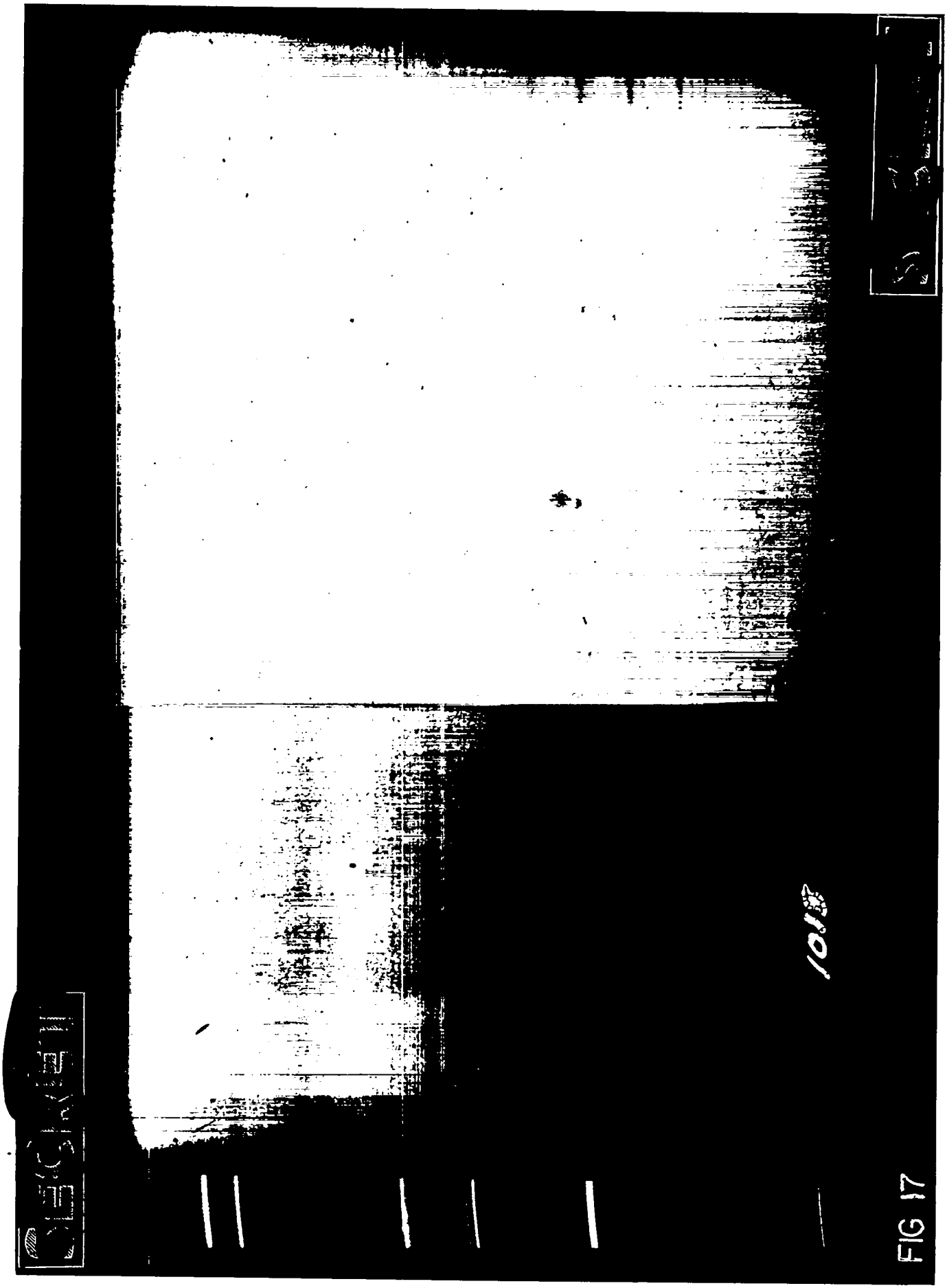
Figure 17

Composite, showing the beginning and end of the bomb spectrum. The Hg vapor comparison spectrum shows at the very end of the bomb spectrum. (This was a lucky accident). The violet end of the spectrum is here on the right hand side of the figure.



[redacted]

Intensity	λ_{vac} A	ν_{vac} cm^{-1}	No.	Absorption bands and lines	Emission lines
6w	3067	32605	1		
7w	3093	32331	2		
6	3100	32258	3		
1	3127	31980			
1w	3183	31417	4		
1w	3220	31143	5		
1w	3237	30893	6		
1w	3257	30703	7		
4	3289	30404	8		
4	3319	30130	9		
1	3377	29612			
1	3396	29446	10		
9	3427	29180	11		
1w	3521	28401	12		
1	3542	28233			
10	3555	28129	13		
4	3584	27902			
1w	3595	27822	14		
1w	3656	27358	15		
10	3696	27056	16		
1	3717	26903			
1w	3741	26729	17		
2	3762	26582			
3	3814	26219			
7w	3840	26042	18		

Fig. 18

Wavelength Chart
3067 - 3840 Å
Hilger E486 Quartz
Spectrograph
Scale: 1mm = 0.1mm on film

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[redacted]

[redacted]

Intensity	λ_{vac} Å	ν_{vac} cm^{-1}	No	Absorption bands and lines	Emission lines
2	3920	25510			
	3990	25063	19		
1	4005	24969			
	4023	24857	20		
	4065	24600	21		
1	4073	24552			
	4094	24426	22		
	4153	24079	23		
	4222	23085	24		
	4255	23502	25		
2	4291	23305	26		
	4295	23283			
	4342	23031	27		
	4364	22915	28		
	4412	22665	29		
	4504	22202	30		
	4782	20912	31		
	4838	20670	32		
	4905	20387	33		
	4996	20016	34		
	5241	19080	35		
	5429	18420	36		
	5710	17513	37		
	5977	16731	38		

Fig. 19

Wavelength Chart
3920 - 5977A
Hilger E486 Quartz Spectrograph
Scale 1mm = 0.1mm on film

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[redacted]

ν_{vac} cm^{-1}	λ_{vac} A	Intensity	No	Absorption bands and lines
32680				
32552	3060	5	1	
	3072	5	2	
32446	3082	5	3	
31827	3142	1	4	
31646	3160	1	5	
31546	3170	2	6a	
31476	3177	2	6	
31319	3193	4	7	
31201	3206	4	8	
31027	3223	3	9	
31008	3225	3	10	
30788	3248	5	11	
30506	3278	7	12	
30349	3295	3	12a	
30230	3308	7	13	
30157	3310	3	13a	
30102	3322	1	14	
30003	3333	1	15	
29949	3339	2	16	
29851	3350	1	17	
29630	3375	3	18	
29568	3382	2	19	
29507	3389	4	20	
29248	3419	10	21	
28994	3449	5	22	
28944	3455	1	23	
28893	3461	3	24	
28818	3470	3	25	
28736	3480	5	26	
28637	3492	3	27	
28539	3504	2	28	
28482	3511	1	29	
28369	3525	1	30	
28209	3545	10	31	
27996	3572	7	32	
27949	3578	7	33	
27894	3585	7	34	
27878	3587	7	35	
27785	3599	3	36	
27670	3614	5	37	
27578	3626	4	38	
27495	3637	4	39	
27457	3642	1	40	
27375	3653	5	41	
27211	3675	1	42	
27122	3687	10	43	
27042	3698	1	44	
26954	3710	5	45	
26853	3724	7	46	
26745	3739	7	47	
26660	3751	7	48	
26589	3761	1	49	
26539	3768	4	50	

Fig. 20

Wavelength Chart
3060 - 3768A
Bausch & Lomb Small Quartz Littrow Spectrograph.
Scale 1mm = 0.1mm on film

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ν_{vac} cm^{-1}	λ_{vac} A	Int.	No
26427	3784	1	51
26364	3793	1	52
26316	3800	3	53
26089	3833	4	54
26055	3838	2	55
26008	3845	2	56
25934	3856	1	57
25880	3864	4	58
25793	3877	1	59
25750	3882	1	60
25707	3890	4	61
25400	3937	5	62
25316	3950	2	63
25221	3965	3	64
25183	3971	3	65
$\nu_{vac} \times 10^4$	λ (mμ)	Int.	No
2.49	402	2	66
2.48	403	3	67
2.47	405	2	68
2.43	411	1	69
2.42	413	1	70
2.39	420	10	71
2.36	425	1	72
2.35	426	1	73
2.34	428	2	74
2.31	433	1	75
2.30	436	2	76
2.27	440	2	77
2.26	443	4	78
2.25	444	3	79
2.23	449	1	80
2.21	452	1	81
2.20	455	1	82
2.19	457	1	83
2.12	471	1	84
2.09	480	1	85
2.06	485	1	86
2.03	492	1	87
2.0	500	1	88
1.98	506	3	89
1.92	520	1	90
1.86	539	[redacted]	broad absorption band
1.83	547		

Fig. 21

Wavelength Chart
3784 - 5470A
Bausch & Lomb Small Quartz
Littrow Spectrograph
Scale 1mm = 0.1 mm on film

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[redacted]

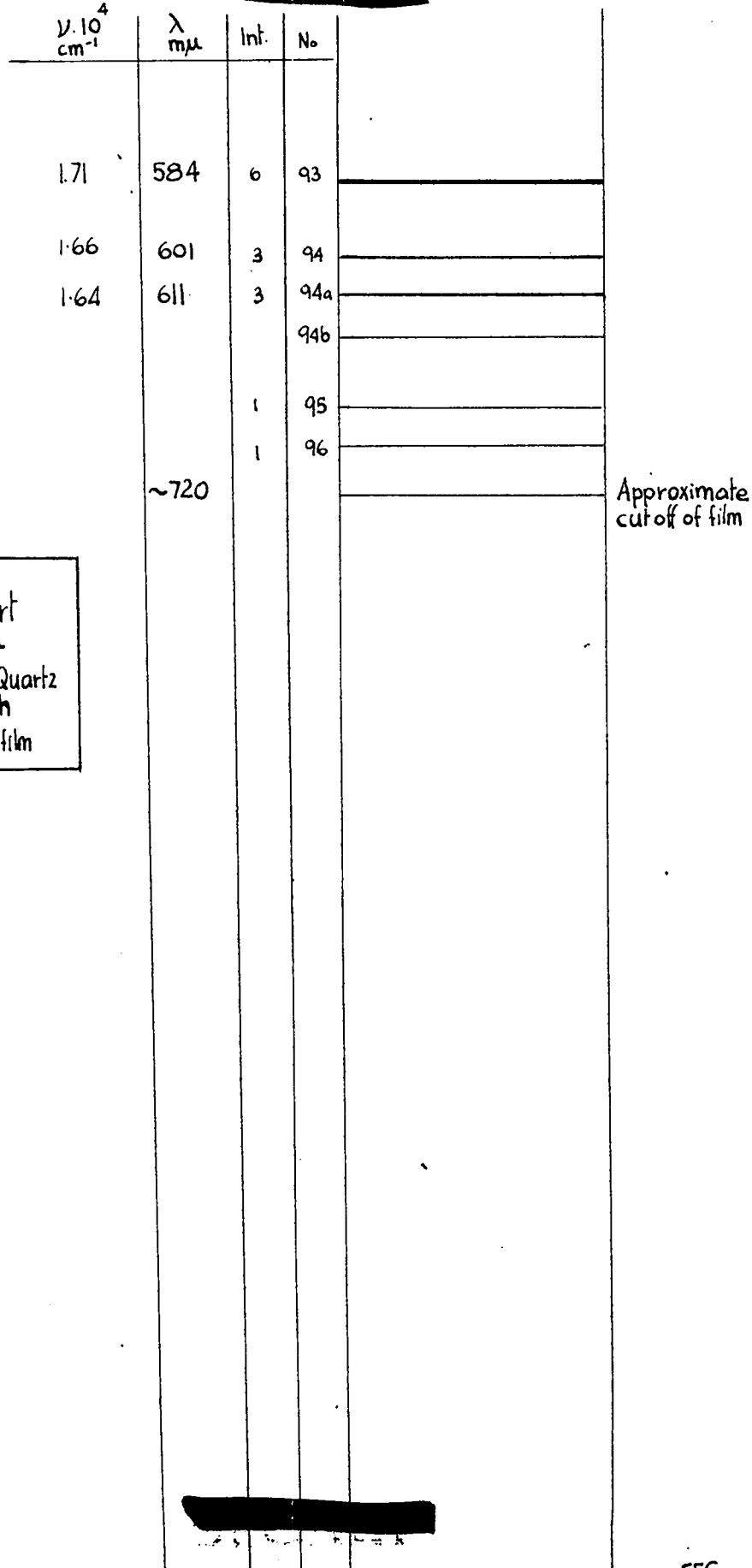

Fig. 22

Wavelength Chart
584 – 720 mμ
Bausch & Lomb Small Quartz Littrow Spectrograph
Scale 1mm = 0·1mm on film

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Figure 23

Spectrum of the bomb taken with the Bausch and Lomb Littrow spectrograph. Time scale, see Fig. 26 for "Time Scale for Bausch and Lomb Spectrogram". Length of record as shown, 0-0.09 seconds. Zero time is at the top, the violet end at the left hand side of the figure. The waviness of the bands is due to the irregular motion of the film transport mechanism and the failure to hold the film in one plane. The dots on the left are caused by an electrical discharge.

[redacted]

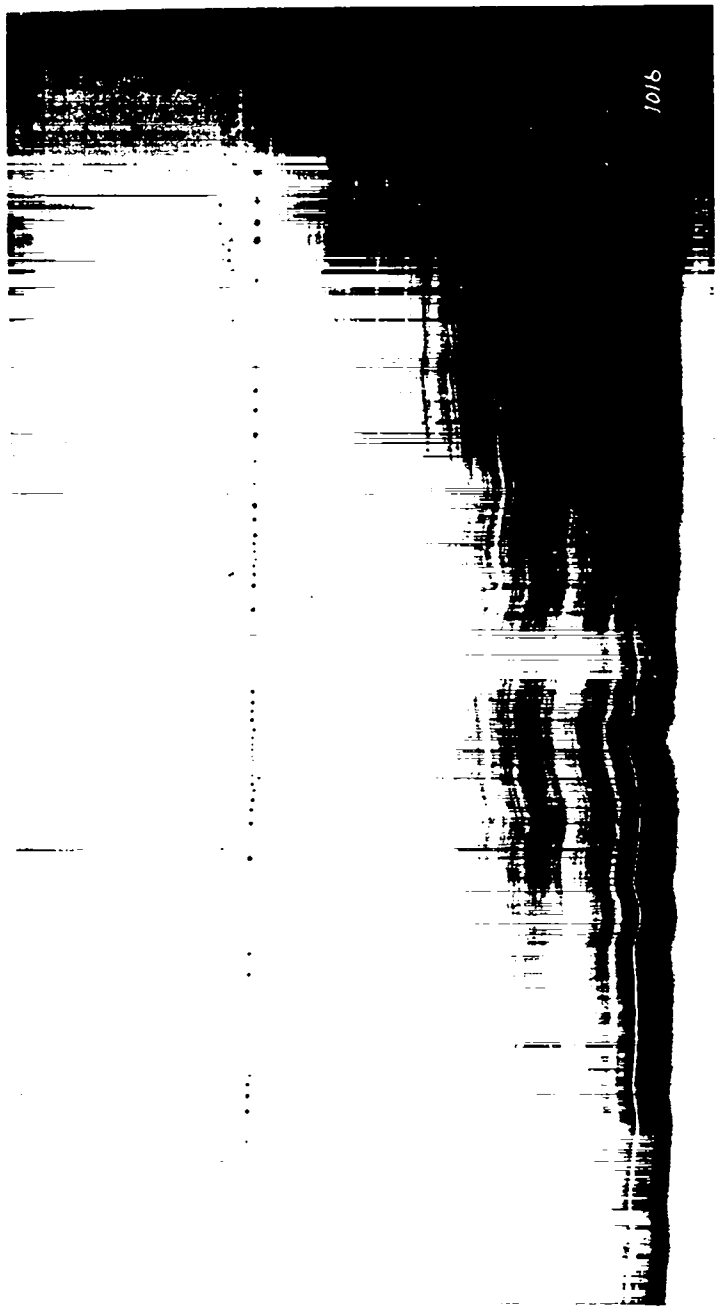

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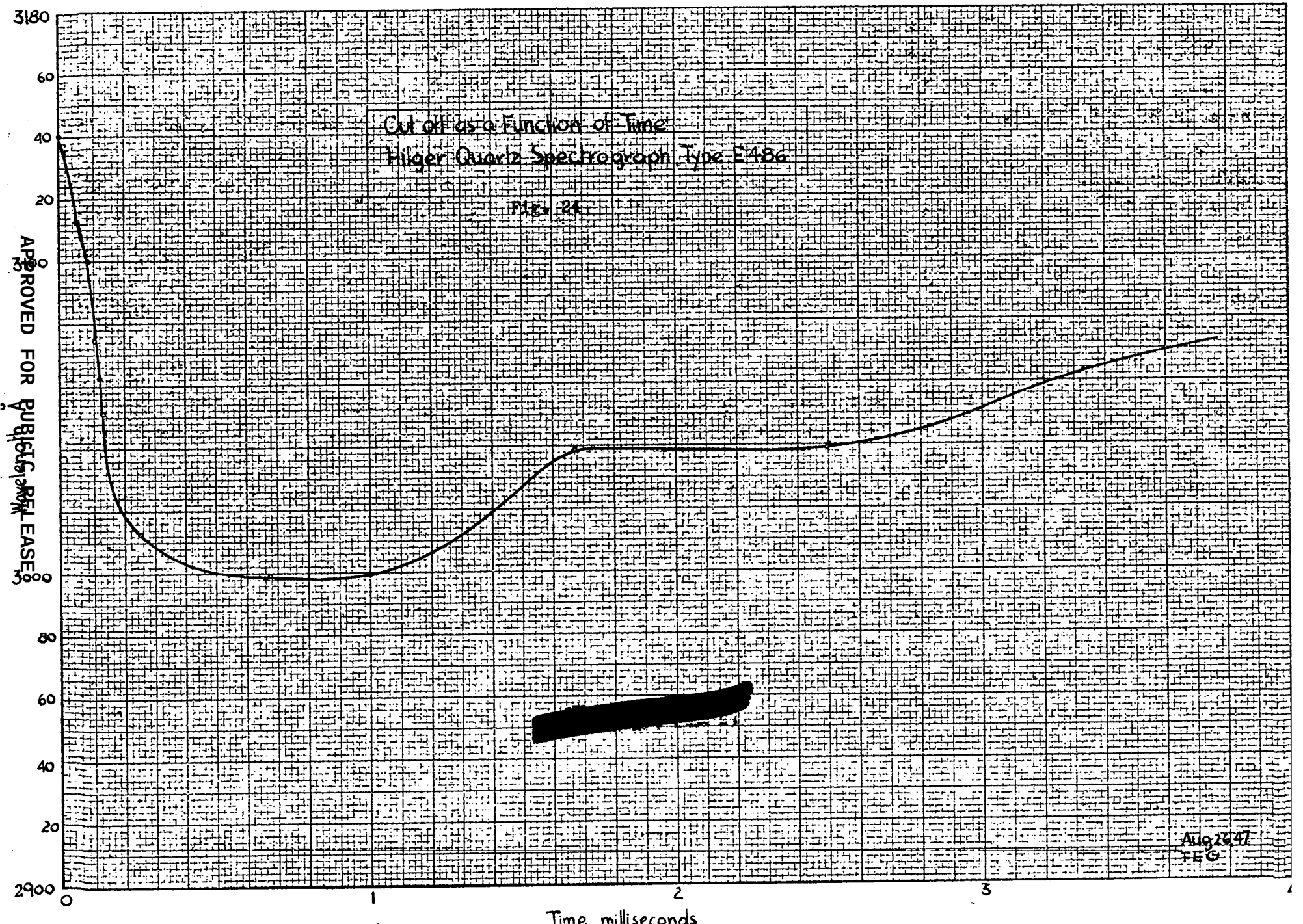
FIG 23



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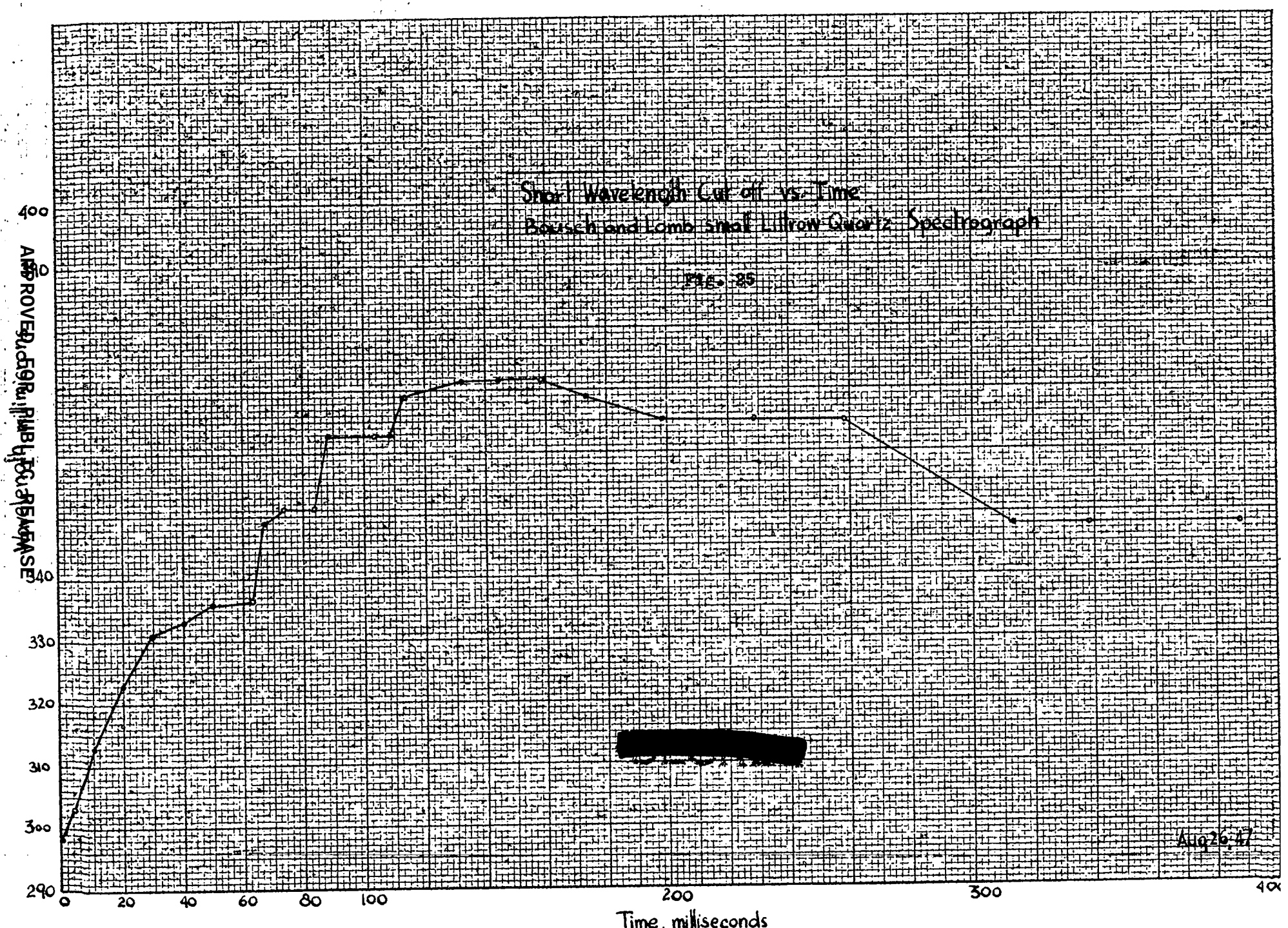
KEUFFEL & ESSER CO., N. Y. NO. 359-11
10 x 10 to the inch, 5th line accented
MADE IN U. S. A.



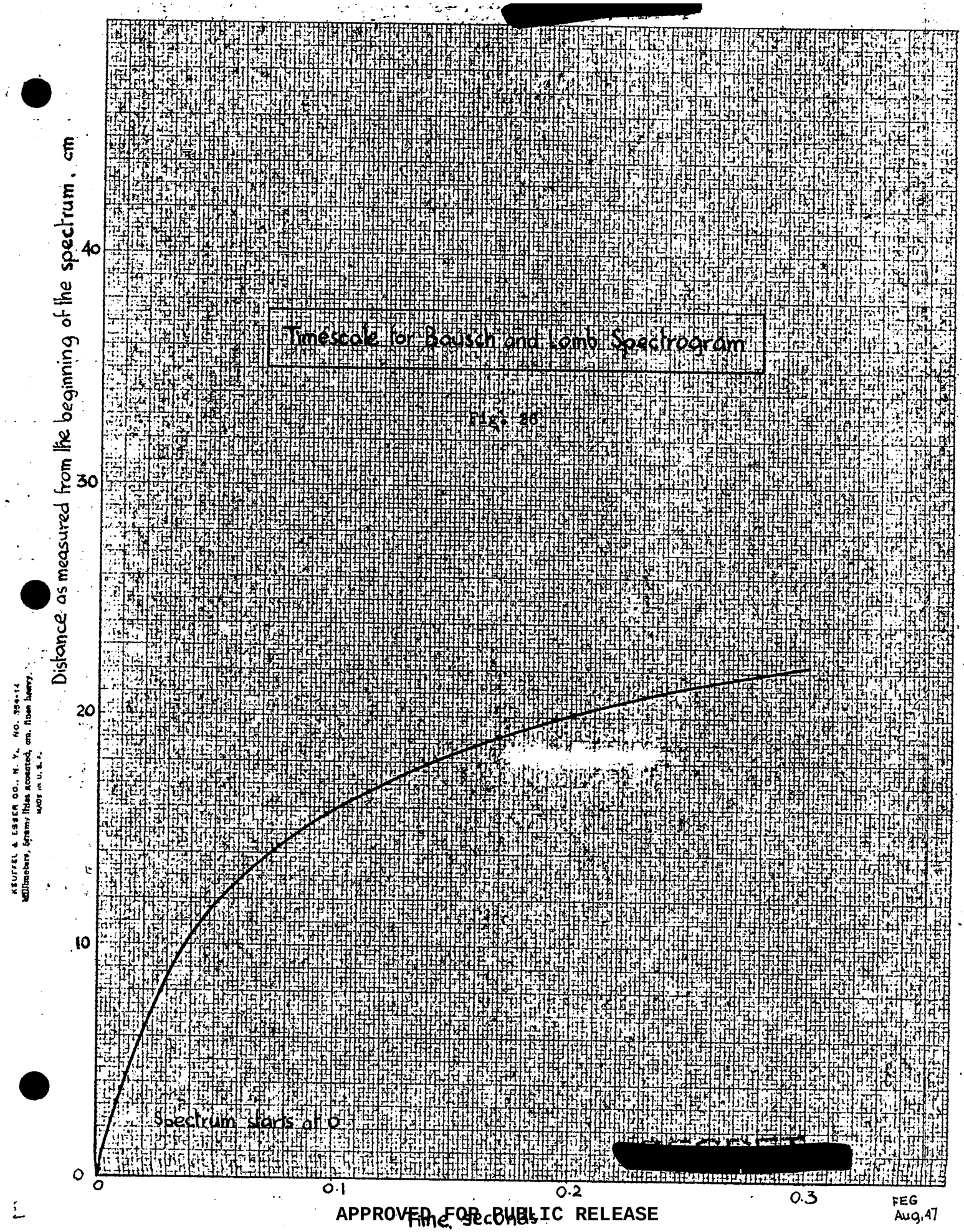


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TABLE I

Table of Temperatures

Time ms	Temperature Deg. K	Density 3470 A	Density 5700 A
0 - 0.038	$5.9\ 10^3$	2.62	3.01
0.038 - 0.071	8.0	3.08	3.30
0.8	12.	3.14	3.30
1.0	5.0	3.08	3.33
1.6	4.9	2.93	3.33
1.72	4.8	2.82	3.30
1.85	5.8	2.81	3.25
2.0	5.6	2.71	3.23
2.3	5.9	2.74	3.22
3.1	5.3	2.47	3.18
5.1	5.0	1.98	3.01

[redacted]

[redacted]

TABLE II

Time Temperature Relationship

O'Brien's original results (in multiples of solar brightness) have been converted into temperatures by J. L. Magee.[1)]

Time ms	Temperature °K
0.15	184,400
0.30	119,250
0.6	64,770
1.0	40,000
2.0	21,800
3.0	16,300
4.0	13,000
5.0	10,860
6.0	9,240
7.0	7,840

---

1) J. L. Magee, Crossroads Report
Brian O'Brien, A Crossroads Technical Instrumentation Report to the Technical Director, August 21, 1946.

[redacted]

[redacted]

TABLE III

Line or Band No. 1), 2)	Appears at sec	Disappears at sec	Changes in structure or appearance of bands
1	0	0.005	
2	0	0.005	
3	0	0.005	
4 and 5	0	0.005	
6 and 6a	0	0.01	appears single from 0 - 0.006 double from 0.006 - 0.01
7 and 8	0	0.01	same as 6 and 6a
9 and 10	0	0.01	same as 6 and 6a
11	0	0.02	
12	0	0.02	
13	0	0.02	
14 and 15	0.01	0.03	
16 - 19	0.006	0.03	
20	0	0.02	
21	0	0.06	
22	0.005	0.06	
23	0.008	0.02	
24	0.006	0.05	
25	0.006	0.05	
26	0.006	0.05	

1) For numbers of lines see "Wave length chart, Bausch and Lomb Spectrograph".

2) A number of lines and bands have been omitted, because the data is not very reliable.

[redacted]

[redacted]

TABLE III

(continued)

Line or Band No. 1)	Appears at sec	Disappears at sec	Changes in structure or appearance of bands
27	0.01	0.02	28 and 29 appear to be single and very broad from 0. - 0.01
28	0.01	0.02	
29	0.01	0.02	
30	0.005	0.06	
31	0	0.06	
32	0	0.13	32, 33, 34, 35 appear as one band from 0 - 0.006, as two bands from 0.006 to 0.02, and as four from 0.02 to 0.13
33	0	0.13	
34	0	0.13	
35	0	0.13	
36	data too unreliable		
37	0.006	0.06	
38	0.006	0.06	
39	0.006	0.06	
40	0.005	0.06	
41	0	0.06	
42	0.005	0.06	
43	0	0.09	
44 - 53	0.005	0.1	
54 - 58	0	0.09	54, 55, 56, 57, 58 appear as One, diffuse line from 0 to 0.006. See Hilger wave length chart, line No. 18.

1) See Bausch and Lomb Wave length Chart

[redacted]

[redacted]

TABLE III

(continued)

Line or Band No.[1]	Appears at sec	Disappears at sec	Changes in structure or appearance of bands
61	0.02	0.06	
62	0.01	0.07	
63	0.02	0.07	
64	0.004	0.08	64 and 65 appear single from 0.004 to 0.02, and double from 0.02 to 0.08
65	0.004	0.08	
66	0.02	0.09	
67	0.006	0.02	
68	0.01	0.06	
69	data too unreliable		
71	0.01	1.5	
77	0.02	1.3	
78	0.01	1.3	
79	0.01	1.3	
80	0.01	0.11	
81	0.01	0.11	
85, 86, 87, 88	0.01	0.11	
89	0.01	0.3	
90	0.01	0.3	
91 - 92	0.02	1.3	
94	0.02	visible to end of record	
94a	0.06	- " -	

1) See Bausch and Lomb Wave length Chart

[redacted]

[redacted]

TABLE IV

Table of Wave Lengths and Limits of Error

Hilger E 486 Spectrograph[1)]

Absorption spectrum

Wave length A
3067 ± 3
3093 ± 3
3100 ± 3
3183 ± 15
3220 ± 15
3237 ± 15
3257 ± 15
3289 ± 2
3319 ± 2
3427 ± 2
3555 ± 2
3696 ± 3
3696 ± 3
3840 ± 6

1) These limits of error were derived from the uncertainty in the readings of the coordinate comparator, uncertainties in the dispersion formula. Some wave lengths seem to have disproportionately large errors. They are due to the use of different methods of measuring. It was not always possible to use the comparator, Spectrum viewers, (least count 0.1 mm), and rulers (least count 0.5 mm) were used in places. Not all wave lengths are listed. Their errors are about the same as those of neighboring listed lines.

[redacted]

TABLE IV

(continued)

Table of Wave Lengths and Limits of Error

Hilger E 486 Spectrograph

Absorption spectrum, (cont'd)

Wave length A
4065 ± 15
4094 ± 15
4222 ± 10
4342 ± 10
4412 ± 5
4782 ± 20
4996 ± 20
5241 ± 25
5429 ± 25
5710 ± 30
5977 ± 35

[redacted]

TABLE V

Table of Wave Lengths and Limits of Error

Hilger E 486 Spectrograph

Emission spectrum

Wave Length A
3127 ± 3
3377 ± 4
3542 ± 5
3584 ± 5
3717 ± 5
3762 ± 5
3814 ± 6
3920 ± 6
4005 ± 6
4073 ± 6
4291 ± 7

[redacted]

TABLE VI

Table of Limits of Error for Wave Lengths Obtained From Bausch and Lomb Spectrograph

Wave Length A	
610 - 584	± 7.5 mμ
547 - 500	± 6.0 mμ
490 - 480	± 4.0 mμ
470 - 449	± 3.5 mμ
440 - 402	± 3.0 mμ
4000 - 3750	± 25

Errors for wave lengths from 3740 - 3060 A may be obtained by direct comparison with lines and bands obtained with Hilger E 486 spectrograph.

TABLE VII

Ultraviolet system of O_3. Measurements of Fowler and Strutt[1], compared with wave lengths obtained with Hilger E 486 Quartz and Bausch and Lomb Littrow Spectrographs.

Fowler and Strutt λ A	Intensity[2]	Hilger E 486 λ A	Intensity[2]	Bausch and Lomb[3] λ A	Intensity[2]
3432.2	1				
3421.4	1				
3402.6	1				
3377.7	1				
3374.1	3				
3365.2	1				
3346.0	1				
3338.5	4				
3331.2	1				
3311.5	5d	3319	4	3318	7
3304.1	3				
3284.0	2	3289	4	3288	7
3279.8	8d				
3272.0	3				
3255.5	5	3257	1w	3258	5
3249.7	8				
3243.0	1d				
3232.8	1	3237	1w	3235	3
3227.2	10			3233	3

1) P.R.S, 93, 577, 1917

2) Intensities on a scale of ten.

3) All Bausch and Lomb readings have been increased by 10 A to conform with Hilger measurements.

TABLE VII (cont'd)

Fowler and Strutt λ A	Intensity	Hilger E 486 λ A	Intensity	Bausch and Lomb λ A	Intensity
3221.5	10	3220	5	3215	4
3206.8	2			3203	4
3201.0	8d				
3194.8	6				
3188.8	1			3187	2
3181.5	1	3183	4	3180	2
3177.0	8d				
3171.6	4			3170	1
3162.6	2d				
3156.1	8			3152	1
3137.4	10d				
3114.3	8d				
3105.0	5	3100	3	3092	5
3096.5	4	3093	2	3082	5
3089.5	8d				
		3067	1	3070	5

[redacted]

TABLE VIII

Ultra violet absorption of mixtures of NO, NO_2, H_2O at normal temperatures,[1] and absorption bands obtained from the explosion of a CO - H_2O - NO medium at high pressures[2], compared with bands obtained with Hilger E 486.

NO - NO_2 - H_2O medium	Intensity (on scale of 10)	CO - NO - H_2O medium	Intensity (on scale of 3)	Hilger E 486	Intensity (on scale of 10)
3843	5	3845	1	3840	7w
		3726	2	3741	1w
3681	10	3680	3	3696	10
3660	1d	3656	1	3656	1w
		3575	0	3595	1w
3539	9	3545	3	3555	10
3510	1	3513	1	3521	1w
		3440	0		
3416	8	3418	3	3427	9
3388	2	3390	1	3396	1
3307	2	3305	0		
3278	1	3270	1		
3207	1d	3202	0		
3177	1d	3183	0		

1) Melvin and Wulf, J. Chem. Phys., 3, 755, 1935

2) Newitt and Outridge, J. Chem. Phys., 6, 752, 1938

[redacted]