Methods for the Measurement of Smoke.

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Chapter I. Object.

The object of this thesis is to compare and to discuss various proposed methods for the determination of the "quantity of smoke" emitted in a given time, from a chimney carrying off the products of combustion of coal fires. By the phrase "quantity of smoke" is meant the quantity from the 'smoke nuisance' point of view, that is quantity as measured in terms of the light absorbing or dirtying power of the smoke, not the volume of the flue gas or the weight of the solid particles therein contained, although the latter may be nearly proportional to the light absorbing power.

By this comparison of methods and the consideration of the faults of each, we hoped to ascertain which may be the most suitable one from a practical as well as a theoretical point of view. Should any method give indications of superiority, it was intended to expend enough thought and time in the construction of the required apparatus, to have it, if possible when finished, a machine of practical utility.

All methods which have been proposed, as far as we have been able to discover, fall under one of two headings :- either I Photometric or II Gravimetric. Those falling under the former heading measure the density of the smoke in the desired kind of units, ie; light absorbing units. Those falling under the latter heading must give results in units of weight, such as the weight of the solid matter per cubic foot of flue gas or the weight of solid carbon per cubic foot of flue gas. Therefore to compare the results given by a photometric method with those given by a gravimetric method, the relation between the weight of solid matter, or the weight of solid carbon, in a units volume of smoke and the light absorbing power of the same, must be known. To investigate the relations between these quantities by experiment would require an extended study of smoke produced under varying conditions for various kinds of coals. However since in our experiments the smoke examined came out of the same chimney, from the same grates, fired with the same kind of coal by the same men, and in fact under very similar conditions, it may be assumed with but slight error that the light absorbing power of a cubic unit of the flue gas is proportional to the weight of solid matter contained in it.

Chapter II History.

During the past century, the great increase of the industries all over the world and the concentration of the same into great centres, has created many new and perplexing problems, important among which, is the so-called "Problem of Smoke Nuisance". Every important city in any of the more advanced nations today, has some form of ordinance regulating the quantity of smoke issuing from sources within it's limits. Most of these ordinances however, mean little or nothing, for they depend upon a visual standard which exists in the mind of some person appointed for this special branch of inspection. As an illustration of this, will be given the following:— Interpretation of English laws; black smoke is a nuisance if emitted for the following times.

Manchester---	1 minute	per	30	minutes
Oldham-----	9 "	"	60	"
St. Helens----	5 "	"	"	"
Newcastle on Tyne-	5 "	"	"	"
Leeds ---------	5 "	"	"	"
Sheffield------	6¼ "	"	"	"
Birmingham--	15 "	"	"	"

Thus the necessity for careful experiment in this direction, is readily appreciated, but as yet very little of a scientific nature has been attempted. The most natural way to solve this problem, is to discover a means of preventing the production of smoke during combustion, and so eliminate the nuisance arising from this cause, and along this line considerable research has been carried on, with good results in some cases. Many forms of 'economisers', 'smoke consumers', reversed draught, steam jets etc, have been devised and used with this end in view, and some of these have succeeded in considerably reducing the quantity of smoke during combustion, but as yet, none of these has succeeded in reducing this quantity to zero.

Engineering Societies in different sections of this country and abroad have investigated and discussed this problem many times but almost invariably in the direction just mentioned above. In the precise direction in which there seems to be the greatest need of investigation, ie;- investigation with the object of measuring the quantity of smoke in any case, and for establishing an accurate standard for purposes of comparison, very little has been done.

However, methods have been proposed and tried, with the view of accomplishing this end, these methods will be described here but will be discussed later.

*I. Doubtless some private experimentation has been carried on of the nature last stated but the only published account which we have been able to find is one given in a pamphlet entitled,—"Bericht über die Sitzung der Commission zur Prüffung und Untersuchung von Rauchverbrennung Vorichtungen" Berlin den 30 April 1894. A method was devised and a suitable apparatus constructed, with which careful experiments were made and good results obtained, the essential features of these are as follows:— the method was a photometric one and the observations were taken of the smoke, as it passed through the main flue leading from the furnaces to the chimney, of the plant at which the research was carried on. The method consisted briefly, in comparing light from a source of known intensity, diminished by passing through the smoke in a path of known length, with light of known intensity from another source, unobstructed by the smoke. The actual photometer used was quite complicated and is best understood from the description in the article above referred to. Holes were made diametrically opposite each other in the main flue and through these a tube 5 centimeters in diameter was passed, at one end of which was placed the reference light, and at the other end the photometer, both of these were external to the flue. A slit was cut in the tube, of a length sufficient to allow the smoke to pass through it for the entire width of the flue, and in this way the partial obstruction of the light by the smoke, was accomplished. The other details of the apparatus are minor ones and it is not deemed necessary to explain them here, as the principle involved, and the main features, are all that are desired. A modification of this method will be proposed and discussed later.

#II. The next method is one that was used in connection with the thesis of Messrs Atkins and Smith in 1896, and is a gravimetric one, a brief substance of the same is as follows:-

a definite quantity of smoke was drawn from the chimney and through lightly packed asbestos, and in this manner the solid matter in the flue gas was abstracted and afterward weighed. Thus knowing the quantity of flue gas, and also the amount of solid matter therein, the weight of the latter per cubic unit of the former is readily obtained and serves as a measure of the light absorbing power of the smoke. The details of the apparatus used are in short as follows:— a glass tube of about 5/8 of an inch in diameter, one end of which had been drawn out to a smaller diameter, was packed lightly with thoroughly dried asbestos, which was prevented from issueing at either end, by small pieces of copper gauze. The small end of this tube was inserted into a small brass stuffing-box, and packed tightly in this with asbestos, connected to the other end of the stuffing-box was a tube, which in turn was connected to a gas meter, this last being connected to an aspirator, which furnished the suction necessary to draw the smoke from the chimney or flue, and through the packed tube. When a test was to be made, the connections were made as stated above, after first having carefully weighed the glass tube containing the asbestos, then this tube was inserted into a brass tube, large enough in diameter to admit the stuffing-box, and this brass tube was then inserted into the chimney, so as to bring the free end of the glass tube well into the interior of the flue. The aspirator was then connected to the water supply, and the whole was then ready for operation. Not very great success attended the experiments made with this apparatus, but this was probably not on account of the faults of the method, but of the apparatus as constructed.

III.

A short account of another method is given in the thesis of Mr. Humphreys 1897. The method and apparatus were as follows :- a number of dull colored glasses were so arranged, that they formed a series, each step consisting of one more peice of glass than the one just preceeding, and thus a scale of various known densities was secured. This scale was suitably mounted in a wooden frame and was then ready for use; the only other piece of apparatus used was an ordinary stop watch. The operation was to view the smoke through the step lowest in the scale which would cause the contrast between the smoke and the sky to disappear, and by keeping a suitable record of the changes, the variations of the density of the smoke were obtained.

IV

Still another method which has been used, employed as an apparatus a scale to which the smoke was directly compared. This scale consisted of a piece of heavy white paper or thin bristle-board, upon which had been ruled a series of black lines, which were uniform in width, these lines were in two sets which were perpendicular to each other, somewhat similar to the form of cross-hatching generally used to denote copper. The scale was separated into divisions in the direction of its length, and each of these divisions contained a greater number of lines per inch than the one just preceding it. When applied, the scale was placed at a short distance from the observer and compared directly with the smoke, record being made of the divisions, corresponding to the density of the smoke at any time.

Mention has been made of various other methods that have been tried by different experimenters, but these have been very brief and no accounts could be found. The methods described above constitute the only ones of which we could find any account, the discussion of these and the modifications proposed, will be given under the succeeding heading.

Chapter III. Discussion of Methods.

It is to be observed, that in order to compare observations made by any method, it is necessary to know the volume of the gas emitted from the chimney during the period of observation. There are two ways in which to find this. The simplest, and the one which first suggests itself, is to place at a convenient place in the chimney an anemometer and a thermometer, read from these the velocity and temperature of the flue gas, and multiplying the velocity reading by the area of cross section of the stack, at the point in question, get the volume of the gas at the temperature read.

Unfortunately, the flue gases are at a temperature that ordinary forms of accurate anemometer will not stand. Besides, the high temperature and the soot soon affect the bearings of any anemometer to such an extent, that their accuracy is not to be relied upon. The other way, and one the necessary data for which are at hand, if the smoke measurement is carried on in conjunction with a boiler test, is as follows:— knowing the weight of coal burned, it's percentage of carbon and hydrogen and the percentage composition of the flue gas, calculate the volume, at the temperature when the observation is made, of the gas which the carbon must have yielded and add to this the volume of water yielded by the burning of the hydrogen of the coal. The result may be in error from inaccuracies in any of the data used, also any air leakage into the chimney above the point at which the samples for the gas analysis are withdrawn, will increase the volume of the gases emitted from the top.

From this it will be seen, that unless the smoke test be carried on in conjunction with a boiler test, we cannot expect to get results by which the smoke from two different chimneys, or from the same chimney at different times, can be very accurately compared. Still there is no reason why with a suitable anemometer, the results could not be relied upon to within a few percent, providing that the density of the smoke can be determined with that accuracy.

Gravimetric Method:— As above stated, any gravimetric method is open to objection, on the score that light-absorbing power is not proportional to the weight of solid matter in the smoke. If the smoke particles were of uniform size and specific gravity, since they are practically opaque, it follows that the light absorbing power would be proportional to the weight. It is difficult to believe that the size of smoke particles issuing from the top of a chimney varies through a very large extent however. It can also easily be calculated, assuming the particles to be opaque and black, that even if the average size of one gramme of smoke particles was twice as great as the average size of another gramme of smoke particles, the light absorbing power would be but 20.6 percent less. If then, this was the only objection to the gravimetric method as described in the previous chapter, it would be the most inviting for experimentation, however, there are other objections. The smoke should not be withdrawn from the uptake or from any point low down in the chimney, for there is no doubt that large particles of carbon are carried to a considerable height by a momentary increase in the velocity of the current of gases, only to drop back again as the draft decreases. A single one of these particles entering the tube to be weighed, an occurrence by no means unlikely to happen, would undoubtedly affect the weight to such an extent as to render the result useless. Now concerning large chimneys, with very few exceptions, it is a practical impossibility to withdraw a continuous sample of smoke from the top or "near the top. This practical difficulty must rule out the gravimetric method from becoming generally useful, however, we were able to use it in our experiments, for we could easily withdraw a continuous sample of smoke from a point in the chimney of the

Rogers Building opposite the fifth floor as there is a plugged hole at that point. The height of this point is some eighty feet above the level of the grate, and since there was but little possibility of the very large particles of unburned coal being carried up to this height, we hoped that the light absorbing power would prove to be nearly proportional to the weight of solid matter, for every volume of gas.

In the gravimetric method as used by Messrs. Atkiss and Smith in 1896, results were not obtained, as the tubes weighed less after drawing the smoke through them than before. This was undoubtedly due to the incomplete extraction of the water from the asbestos used in the tubes; this can be remedied by previously heating the asbestos for a suitable length of time. The asbestos used in our experiments was heated in an open cassarole for forty-eight hours to a temperature of 120° centigrade before use, and even then, it lost when used for a first time, nearly enough weight through further extraction of water to nearly make up for the gain of weight by deposition of soot. As there is no reason to believe that the tubes should not used over without repacking, this was done, with the result that was expected; much less water if any was driven off by the second exposure to the action of the hot flue gases.

Previous experimenters, as well as ourselves, have been greatly inconvenienced by the breaking of the glass tube where it was drawn down. In our first trials of this method, this was caused by the poor form of stuffing box which necessitated undue pressure upon the glass tube. This was obviated by using a piece of thick walled rubber tubing instead of a packing box; this was protected from the hot flue gases by allowing a current of cool air from outside of the chimney to circulate around it, this current of air also cooled down the sample of gas, and thus protected the meter from injury.

The method before referred to as having been used in Germany a few years ago, in the dim light of our present knowledge is beyond reproach as regards accuracy. Even though the results obtained were considered satisfactory, objection can be raised against this method, in that it is necessary to cut two holes in the flue. This may seem at first to be a rather trifling objection, for it is not a very difficult operation to cut two small holes in the flue, and when cut, the holes do no harm if they are left suitably stoppered; nevertheless, it would doubtless be difficult to persuade some manufacturers to allow one to cut holes in their chimneys, especially when it is for the purpose of showing that the smoke emitted from those chimneys is a public nuisance. Another objection is that the apparatus is complicated. However an apparatus on this same principle has been suggested by Professor Lövamb of the Institute, which is much simpler and is worthy of discussion.

If time had permitted, we would have constructed this apparatus and would have experimented with the same, but unfortunately, time has been such a pressing factor, that we were obliged to leave this method, a promising opening for future investigators in this field.

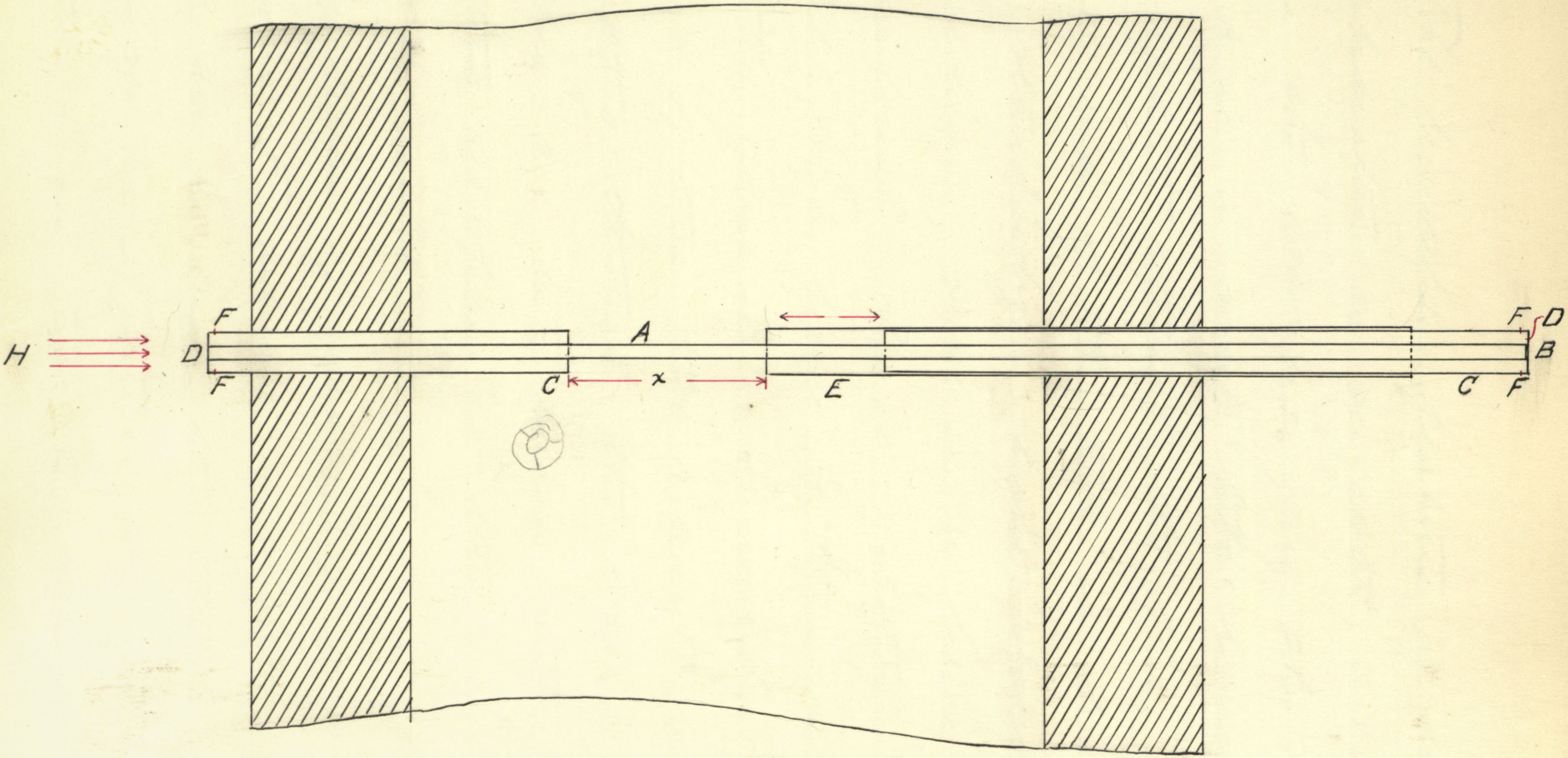


FIG. 1.

The principle features of the apparatus as suggested, are shown in the accompanying sketch.

A is a small tube passing completely through the flue, over one end of this tube is pasted a standardized light absorbing medium, such as a piece of uniformly dense photographic film, or a piece of thin neutral tinted glass, B. Surrounding each end of this tube A, and projecting through the walls of the flue are two larger tubes, C, these are open at the inner ends, and sealed at the outer ends by pieces of glass, D. Small holes, F, admit a slight current of air to enter the tubes C.

Over one of the larger tubes C a still larger tube (E) slides.

Light from H passing through the tube A, and through the film at B, is matched with light from H entering the tube C, and reduced in intensity by passing through the column of smoke of variable length x, this length being adjusted by sliding the tube E in or out.

This method was given by Professor Lévaut only as a suggestion, and of course the details would have to be worked up. Objections which present themselves, although they might be eliminated by modifying some of the details of the apparatus are as follows:—

First, as the smoke grows rapidly denser and the tube E is pushed in to make the column shorter, smoke will enter the open tube E, making the column of smoke an uncertain amount longer than x, unless the current of air entering the chimney through E is very strong. This latter is not allowable, for it would produce eddies in the column of smoke under observation, and render the density measurement inaccurate.

Second, when the smoke is dense, the distance x must be small and as the apparatus must be situated well down in the chimney, or flue, leading to the chimney, the air entering through the furnace doors during the period of firing, and the furnace gases proper will not become thoroughly mixed, hence such great variations in the density of the column of smoke will take place, that the observer will be unable to accurately follow these.

The method referred to in the previous chapter under number IV, is essentially so crude as to make a discussion of it seem almost unnecessary. However, it is a very simple and convenient method for the comparison of smoke issuing from the same chimney, under the same conditions as to the state of the sky. That the light absorbing power of a double cross hatched surface is not proportional to the width of line multiplied by the number of lines to the inch, is readily seen at a glance, but this can be obviated by using ordinary cross hatching, or allowed for by taking the light absorbing power as proportional to the product of the width of line and the number of lines to the inch, minus one half the square of that quantity, the latter term being simply to allow for the area of surface which has been inked over twice, and which is in reality, no more efficient as regards it's light absorbing power, than the portion which was inked but once.

The discussion of the method used by Messrs. Atkins and Smith in 1896 will be given in the succeeding chapter, the reason for this will

be readily seen upon reading
the account in it's connection there.

Chapter IV. An Origional !!! Method.

As stated in chapter I our object was not only to discuss the various methods for the measurement of smoke but also to arrange if possible an apparatus which would accurately serve in this capacity and at the same time be one of practical utility. Taking this last condition into account, the first and simplest method that suggests itself is one of direct comparison, a photometric method. Method III described in chapter II is one which recommends itself at once as a foundation for a more accurate one, chiefly on account of its simplicity.

There is however, the following objection to this method:- as described before, the operation is to view the smoke and a portion of the surrounding sky, through dull colored glasses, and through such a number of these as would cause the contrast between the sky and smoke to disappear; now, this disappearance is due to the fact, that the light transmitted through the dull colored glass is so diminished in intensity, that the difference between the intensity of the light from that portion of the sky closely surrounding the smoke, and the intensity of the light passing through the smoke, becomes inappreciable to the eye. The objection is, that the condition of the sky which forms the background may affect the results considerably. This is apparent if one considers, that the intensity of the light from the sky may vary from that due to sunlight reflected from light fleecy clouds, to that due to dark or dull clouds, with which the entire sky may be overcast.

The results obtained under these different conditions would not closely agree, for, in the former case, if a certain thin piece of glass were used, the light from both the smoke and the sky would be reduced to the intensity which they would have in the latter case with no glass intervening, and the error of density is that of the thin piece of glass mentioned.

The preceeding considerations led us to suggest a modification as follows:— in place of the above operation, the dull colored glass should intercept the light from the sky only, and so diminish it that its intensity would appear just equal to that of the light passing through the smoke. In the <u>origional</u> method, the intention was to use smoked or neutral tinted glass, but the difficulty in obtaining this was so great, that a dull violet glass was substituted. !

As the same defficulty presented itself to us, and dull violet glass could not be used, in our modification of the method, on account of the impossibility of properly matching the gray

The Phys. Dept. had a wedge of neutral-tint glass — but was not consulted by the young men. C.

smoke with the colored scale, we were forced to find a substitute. This substitute was the ordinary photographic film, the treatment of which will be described later in this chapter. In making use of this substitute, it was decided to adopt the photographic wedge to secure the necessary variations of density, such that the light from the sky could be diminished to the degree of intensity, corresponding to that of the light passing through the smoke.

It was decided to produce a wedge of uniformly increasing density for our use, and with this end in view we tried several <u>origional</u> methods, but with no success.

Upon inquiry, we were referred by Mr. Deer of the Institute, to the Harvard University Observatory, where it was understood that photographic wedges were used in astronomical work there. We went to the Observatory and were treated very courteously ~~there~~, Professor Pickering kindly explained the method employed, and offered us the use of the entire apparatus. We adopted the method used there, but we constructed our own apparatus; this was temporary, and consisted of two four by five cameras from which the lenses had been removed, and two pieces of thin cardboard in which had be cut small rectangular slits, the details of the arrangement of the

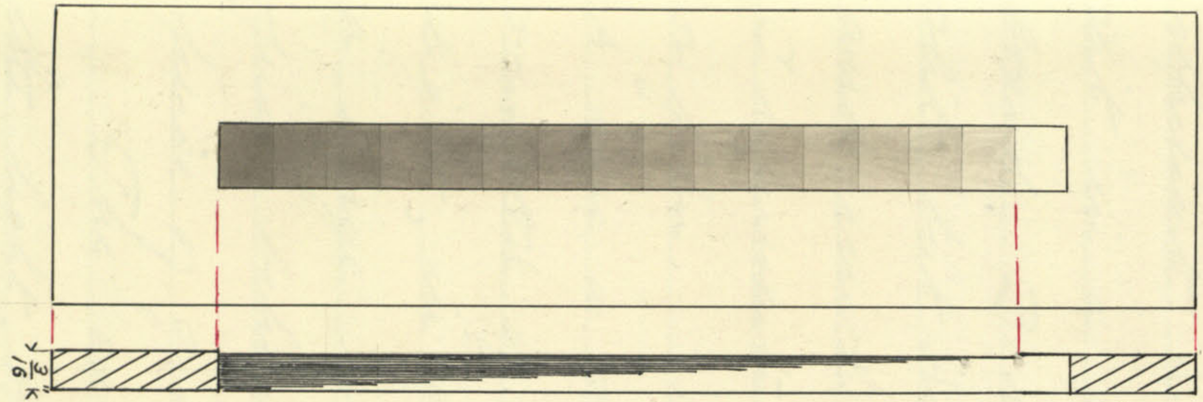


FIG. 2. SCALE 1" = 1½"

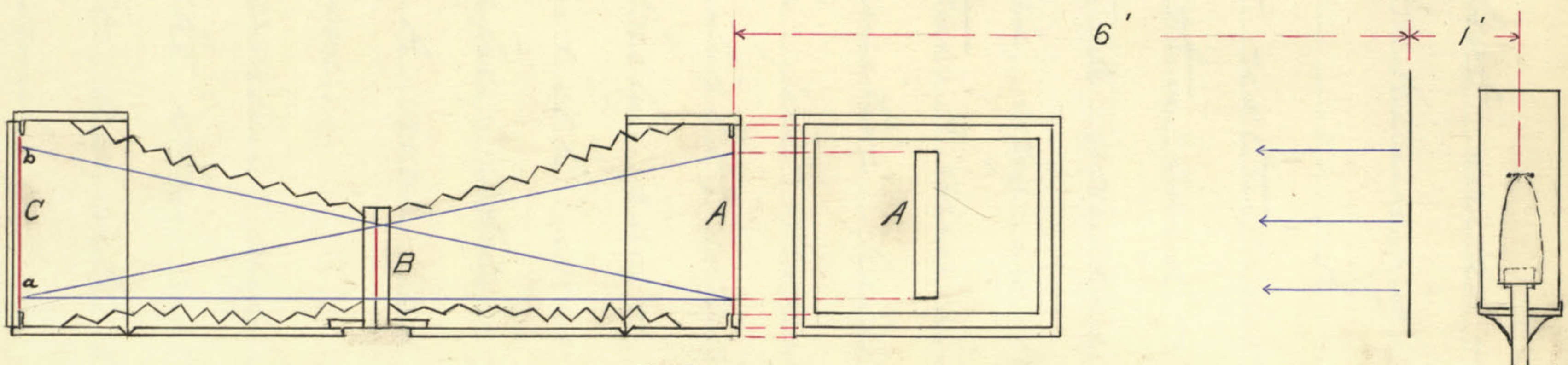


FIG. 3.

apparatus can be best understood from the accompanying sketch, FIG. 3. A represents a narrow rectangular slit in a piece of thin cardboard, B represents a similar slit, but one half as long as A and midway between A and C. C represents the sensitive plate, or film. About six feet from A was a source of light, which consisted of a Welsbach gas-light, in front of which was a large white paper screen; just behind slit A was a piece of ground glass.

The cardboard screen diffused the light, so that the thin rectangular spot of light admitted by A upon the ground glass, which was behind it, and in contact with the same, represented practically a uniformly luminous surface.

Now, by the intervention of the slit B, the light from the uniformly luminous surface or slit upon the ground glass, does not uniformly illuminate the plate at C, but lights up on it a narrow rectangle in which the illumination varies from zero at b, to a maximum at a:- this is apparent from the accompanying diagram.

We applied this apparatus and made several wedges, but upon developing them, each one showed the same phenomenon;- the density instead of being uniformly increasing, increased very rapidly for a short distance, and then remained practically of constant amount for the rest of the wedge.

The cause of this is, that the density of a negative is not proportional to the exposure which it has been subjected to, so, without knowing the relation existing between "exposure" and "density", we could not hope to make a photographic wedge of uniformly increasing density.

It was therefore decided, that we might make an approximation to such a photographic wedge, which would serve our purpose just as well; the following is a description of the substitute and the way in which it was made.

An ordinary photographic film, fresh and unexposed, was repeatedly passed through strong developer until the silver commencing to precipitate, caused the film to assume a light greyish color. The development was then discontinued, and the film was fixed, washed, and dried, in the usual manner. The film now appeared of a uniform light grey tint, and when viewed against the sky, should be of about the density of smoke, so thin as to be barely worthy of consideration.

We had some difficulty in attaining this last condition, because the degree of development had to be judged by eye, and could not be timed, because, although the developer used was always of the same strength, there are several other factors which cannot be maintained constant, such as, the variation of the light used in develope-ment, the sensitiveness of the film, etc.

The next operation was to cut the film up into strips 3/4 of an inch wide, and of different lengths, these lengths were multiples of a constant length determined by the di-mensions of the wedge, in our apparatus this constant length was equal to 5/12 of an inch:- this means that one strip was cut equal to this length, another to twice this length, and so on. These lengths were then placed upon each other in order, and they then formed a density scale, which was analogous to a photographic wedge, but differed from it, in that the variations had an appreciable length, namely, $\frac{5}{12}$ of an inch:- the arrangement can best be seen from the accompanying diagram.

The strips arranged in the order described were then fastened together by a small amount of glue applied at the corners of each strip, then the bottom and longest strip was glued at the edges to a peice of thin cardboard, over a rectangular opening which had been previously been cut in the same,

$\frac{1}{2}$ of an inch wide, and $\frac{5}{12}$ of an inch longer than the longest strip. A second piece of cardboard, in which had been cut an opening of the same length but $\frac{3}{4}$ of an inch wide, was then glued over the first, so that the glued strips of film just fitted into the opening.

A third piece of cardboard, having an opening of the same dimensions as the first piece, was glued over the last and the whole was then firmly held in place. The reason that the openings in the pieces of cardboard were one division longer than the scale, was to provide an opening which would correspond to the condition of zero density of smoke.

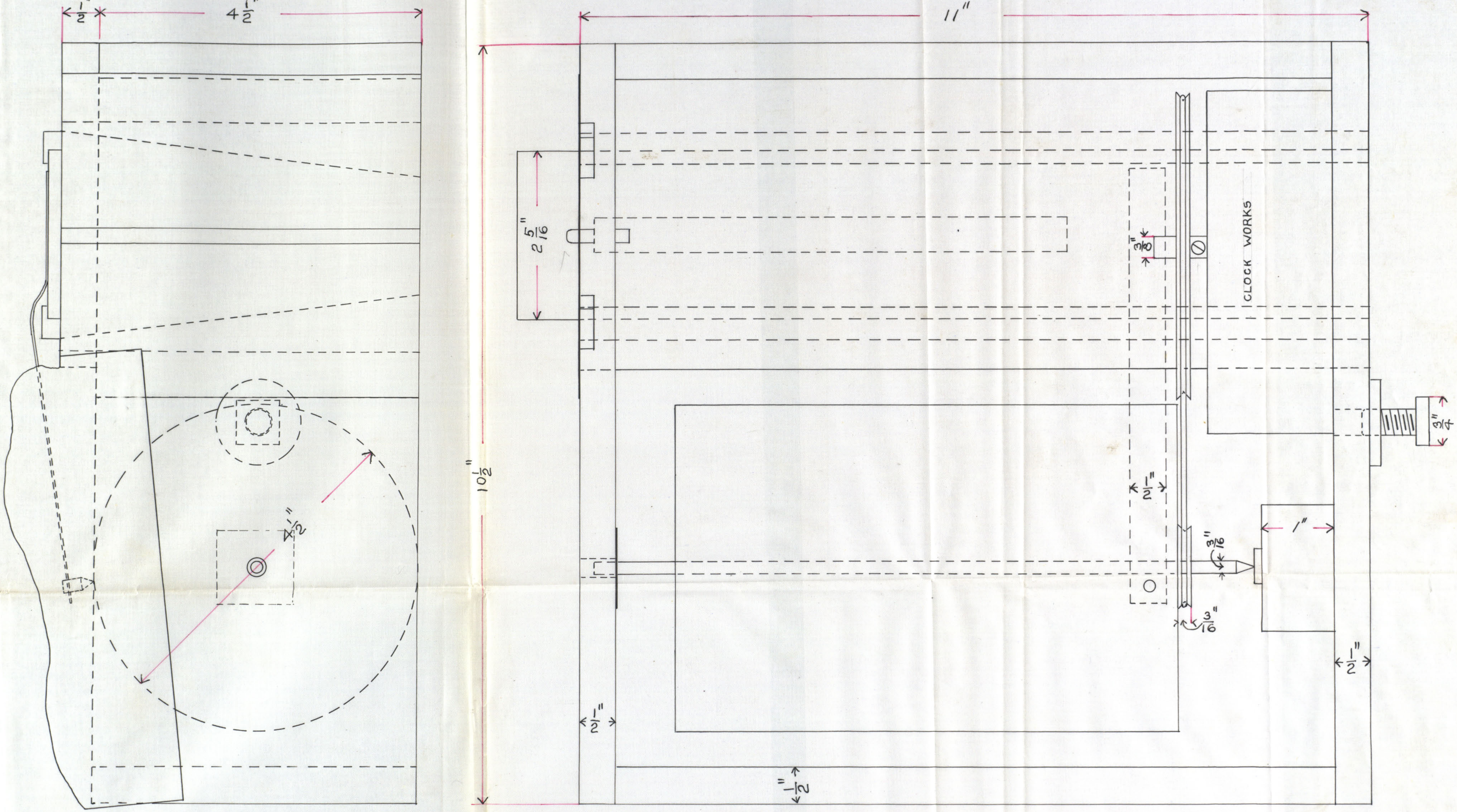
We next desired to make the apparatus recording. This was done in the usual way, by making use of a drum, driven with a uniform velocity, by a suitable clock work. In order to diminish the friction, the drum was mounted in jewel bearings.

One end of a thin flat piece of steel was fastened to the bottom of the scale, and into a small hole in the other end of the piece of steel was forced a short piece of a copying pencil. The steel arm was curved, so as not to interfere with the other parts of the apparatus, in it's path up and down; and served, by virtue of it's elasticity, to keep a steady pressure upon the pencil, which was in contact with a paper on the surface of the drum. Upon this paper, the pencil traced a line, the distance of which from the bottom of the drum, varied as the scale was moved up or down. Thus, the area between this line and a zero reference line, divided by the length of the zero line, will give the height on the scale, corresponding to the mean density of the smoke.

In our first apparatus, constructed in this way, it was found difficult to match the smoke, as it was, surrounded by the bright light of the sky, with any point or division in the scale, for the latter was not so contrasted. To overcome this difficulty, we observed the smoke through a narrow tube, of such length, that only a small area of smoke could be seen through it, and none of the surrounding sky. In order to make the conditions of comparisons just the same, the density scale was observed through a similar tube.

In making the apparatus used in our experiments, it was thought advisable to have three divisions of the scale in sight, the middle one being the one that matched the smoke, the other two serving only as guides, to indicate where it was necessary to move the scale. In our experiments, however, it was discovered that the density of the smoke from the chimney of Rogers Building varied so rapidly, that one did not have time to look at more than one division of the scale, when observing. Nevertheless, it was found convenient when the chimney was just starting to smoke, to be able to see both the zero, and the number one division of the scale, so as to know just when to start to move the scale.

To increase the accuracy with which the smoke could be matched, the instruments were provided with hoods, made of rubber coated cloth, which could



SCALE FULL SIZE.

FIG. 4.

be put over the observers head to exclude the daylight, similar to the focussing cloth used in photography. These hoods are not shown in the accompanying tracing, but they were simply rectangular pieces of cloth, one edge of which was permanently pasted to the top of the frame of the apparatus. Hooks and eyes were provided, so that the hoods might be raised when not in use and fastened at the bottom when in use. This provision was found to be necessary, on account of the trouble experienced from the wind.

The whole apparatus when completed was arranged so that it could be mounted upon an ordinary tripod, which formed a firm, and at the same time adjustable, support for the same.

Two of these apparatus, described above, were constructed alike in every detail, in order that independent observations might be taken by different persons, at the same time, and from different positions;- thus putting the efficiency of the method to a practical test.

Chapter V. Experiments.

As a preliminary test of our method, and also as a guide to the details of our final apparatus, a rather crude one was first constructed. Our first experiment was made with this apparatus, upon smoke issuing from the chimney of the Engineering building of the Institute. The record taken, was faint, but indicated that good results might be obtained with a well constructed apparatus.

The new apparatus were constructed, and our first experiments with these were made upon smoke from the chimney of the Rogers Building. The instruments were placed upon the roof at two points some distance apart, and from these positions simultaneous observations were taken by two persons.

During the first run, considerable trouble was experienced from the wind, which prevented the hoods from performing their function of keeping out the daylight, so that these first records proved to be of little value. The difficulty first mentioned, was overcome as stated in the description of the apparatus, by fixing hooks and eyes to the hoods and the frame of the apparatus, so that the hoods might be fastened down when in use.

The second test was successful as regards records, but one trouble, which existed through all of our experiments, was encountered; the trouble arose from the fact that very little smoke is emitted from the chimney of the Rogers Building, and what little is emitted, is in very short sudden puffs, lasting generally for about twenty seconds, and sometimes for only a few seconds. This, of course, necessitated very rapid matching, which consequently impaired the accuracy of the work. Hence, under these severe conditions, it is not surprising that some of the records, which were taken simultaneously, do not agree more closely. A discussion of the records taken, and the results, will be given in the succeeding chapter.

After several tests, it was decided that density scales, somewhat darker than the first ones used, would be an improvement, as the darkest divisions of the first ones were scarcely dense enough to correspond to very black smoke. Accordingly, two new density scales were made, somewhat darker in tint than the first ones. In order to be certain that the density of any division of one scale, should be exactly equal to the density of the corresponding division on the other scale, a piece of film was developed, large enough to permit of making both scales from it.

In addition to the comparative tests of the two apparatus, we desired to check our method by another method and for this purpose selected the one used by Messers. Atkins and Smith in 1896, described as the gravimetric method. The arrangement of this apparatus as we used it was described in chapter III.

When a test was to be made with both kinds of apparatus, the tripods, and the instruments fastened to them were placed in the desired positions, an anemometer which was fastened to a piece of timber, was inserted into the top of the chimney, the asbestos packed tube was connected to the meter and inserted into the chimney, and then the aspirator was started, the exact time of which was noted. Simultaneous records were taken with the apparatus upon the roof, the time of starting and stopping being recorded, and also the readings of the anemometer at these times. As there was so very little smoke, the drums were sometimes allowed to revolve three times before the test was stopped. Three observers were necessary, one to read the anemometer and the other two to manipulate the apparatus on the roof. Four observers would have been better, but as it was so difficult to secure extra ones, the order was, to start the aspirator and note the time, then proceed to the roof and take records there, and when these were completed, one observer immediately went down, and shut off the aspirator, and withdrew the tube from the chimney; he also noted the time. The additional time, during which the gravimetric was running, is accounted for, in the calculations. These tests were of about forty-five minutes duration.

We very much desired to take some records of a chimney which smoked quite constantly, and selected for this purpose, the chimney of the West End Power Station, on Albany street. We secured permission to take observations from the roof of the Emerson Piano factory, just adjoining the power station. We set up the apparatus, but experienced considerable difficulty from the strong wind which was blowing, at the time. We were somewhat disappointed also, because it was necessary to make our observations during this test, in the afternoon, and at a time when load upon the station is light, so that the smoke from the chimney was very much thinner than we had anticipated.

Chapter VI. Discussion of Experiments.

Linear velocity of drums:—

The linear velocity of the drums was tested in a room before use in the experiments on smoke, and found to be practically constant. It was desired, however, to know, if when subjected to irregularities of pressure due to the wind blowing upon the shade or hood against the drum, they would still run with a uniform velocity. To learn this, we measured the lengths of each of the record cards obtained in our experiments, and divided each length by the time required for the run. The results thus obtained are tabulated upon the following page.

Drum A.

Experiment	Total length of card in inches L	Time required T	Velocity = $\frac{L}{T}$
I	13.98	13	1.074
II	32.00	31	1.032
* III	13.61	13	1.047
* IV	40.89	40	1.022
* V	41.25	40.5	1.018
* VI	42.81	41.75	1.024
* VII	13.50	13	1.038
VIII	11.53	11	1.048
IX	14.86	14	1.061

Drum B.

Experiment	Total length of card in inches L	Time required T	Velocity = $\frac{L}{T}$
I	14.34	13	1.102
II	31.68	31	1.022
* III	14.15	13	1.088
* IV	42.82	40	1.071
* V	42.89	40	1.072
VI	Record lost before measured	41.75	——
VII	13.95	13	1.073
VIII	11.74	11	1.067
IX	14.49	13.75	1.053

It will be seen from the foregoing table, that in the first experiment both drums seem to have been running faster than they did in the following experiment. This was because the time was not taken very carefully in that experiment, it was probably about thirteen minutes and twenty seconds, instead of thirteen minutes. In those experiments marked with an asterisk (*), the record paper was purposely put on the drum backwards, in order to stop the clock-work at the end of each revolution, by the projecting edge of the card meeting the pencil. When the clock stopped, the operator lifted the pencil and started the clock again, noting the time.

Of course some time was lost in this way, and this accounts for the decrease in the velocity of the drum, but if the operator was watching for it, he could tell just when the clock commenced to slow down, and then he would lift the pencil. The operator of B did this in nearly every case, hence the drum B showed no decrease of velocity in experiments IV and V.

In experiments III and VII, drum A did not make a complete revolution, hence no decrease in velocity was noticed. The same is true of drum B, in experiment III.

Taking these remarks into account, and also the fact that in experiment II drum B was accidently stopped for an unknown length of time, it will be seen that the velocities vary by but one percent from the mean. That this was due to accidental movements of the regulator on the clock works, between experiments, or to the unequal pressure of the pencil in different experiments, and not to the influence of the wind, is conclusively proved by the results of experiments IV and VII. The former was performed upon a very quiet day, and the velocity of each drum is practically identical with that obtained in the latter experiments, which was carried on in a wind so strong, that the tripods upon which the apparatus were mounted, had to be held by the operator in each case, in order to prevent them from being overturned.

On the following pages, will be given the data taken during our experiments and the discussion of the same, the records will be found at the end of the thesis

Data—

Experiments for the comparison of the similar apparatus A and B.

$v_1 = 1.045$ = velocity of drum A.

$v_2 = 1.071$ = velocity of drum B.

Experiment I

No. of puff.	a = area under curve corresponding A	B	l = length of the same A	B	$\frac{a}{l}$ = mean height A	B	$\frac{l}{v}$ = time in mins. A	B	$\frac{a}{v}$ = area if velocity had been unity. A	B
1	—	—	—	—	—	—	—	—	—	—
2	1.00□"	1.07□"	.41"	.41"	2.44"	2.61"	.39	.38	.956□"	.999□"

Experiment II

No of puff	a □" A	B	l " A	B	$\frac{a}{l}$ " A	B	$\frac{l}{v}$ A	B	$\frac{a}{v}$ □" A	B
1	.43	.46	.47	.40	.91	1.15	.45	.37	.412	.429
2	.06	.06	.19	.18	.32	.33	.18	.17	.057	.056
3	1.38	1.44	.78	.78	1.77	1.85	.75	73	1.3217	1.343
4	.78	.68	.57	.38	1.37	1.79	.54	36	.746	.635
Total	2.64	2.64	2.01	1.74	1.31	1.52	1.92	1.62	2.44	2.46

Experiment III

No of puff	a □" A	B	l " A	B	$\frac{a}{l}$ " A	B	$\frac{l}{v}$ A	B	$\frac{a}{v}$ □" A	B
1	—	—	—	—	—	—	—	—	—	—
2	1.92	2.10	1.63	1.42	1.18	1.47	1.56	1.33	1.838	1.960
3	.30	.36	.31	.24	.97	1.50	.30	.22	.278	.336
Total	2.22	2.46	1.94	1.66	1.14	1.48	1.86	1.55	2.125	2.296

Experiment IV   Record too light to planimeter.

Experiment V

No. of puff.	a □" A	B	l" A	B	a/l" A	B	l/v A	B	a/v □" A	B
1	1.04	.78	1.14	1.08	.91	.72	1.09	1.01	.995	.727
2	.61	.45	.70	.74	.87	.61	.67	.69	.583	.420
3	1.26	1.16	2.23	1.77	.57	.66	2.13	1.65	1.205	1.081
Total.	2.91	2.39	4.07	3.59	.72	.67	3.89	3.35	2.783	2.228

Experiment VI

No. of puff	a □" A	B	l" A	B	a/l" A	B	l/v A	B	a/v □" A	B
1	.30	.24	.62	—	.48	—	.59	—	.287	.224
2	1.46	1.46	2.03	—	.72	—	1.94	—	1.395	1.362
3	.04	.04	.22	—	.18	—	.21	—	.038	.037
4	.08	.08	.24	—	.33	—	.23	—	.077	.075
5	22	.26	.26	—	.85	—	.25	—	.211	.243
6	28	.20	.49	—	.57	—	.47	—	.268	.187
7	—	—	—	—	—	—	—	—	—	—
Total.	2.38	2.28	3.86		.62		3.695		2.276	2.128

Experiment VII

No. of puff	a □"		l"		$\frac{a}{l}$ "		$\frac{l}{v}$		$\frac{a}{v}$ □"	
	A	B	A	B	A	B	A	B	A	B
1	1.64	1.50	3.35	3.70	.49	.41	3.21	3.45	1.569	1.400
2	1.04	.70	2.00	1.52	.52	.46	1.91	1 42	995	.653
3	1 86	1.52	2.57	2.14	.73	.71	2.46	2 00	1 780	1.418
Total	4 54	3.72	7.92	7 36	.57	.51	7 58	6 87	4.344	3.471

Experiment VIII

No. of puff.	a □"		l"		$\frac{a}{l}$ "		$\frac{l}{v}$		$\frac{a}{v}$ □"	
	A	B	A	B	A	B	A	B	A	B
1	2.36	1.94	.70	.61	3.37	3.18	.67	.57	2.258	1.810

Experiment IX

No. of puff.	a □"		l"		$\frac{a}{l}$ "		$\frac{l}{v}$		$\frac{a}{v}$ □"	
	A	B	A	B	A	B	A	B	A	B
1	.72	.64	.48	.23	1.50	2.78	.46	.21	.689	.597
2	.66	.45	.55	.50	1.20	.90	.53	.47	.632	.420
3	.40	.26	.33	.28	1.21	.93	.32	.26	.383	.243
4	2.78	2.70	1.34	1.32	2.09	2.04	1.28	1.26	2.658	2.520
5	.74	1.00	.34	.28	2.17	3.57	.33	.26	.708	.934
Total	5.30	5.05	3.04	2.61	1.74	1 94	2.91	2.47	5.070	4.714

Data from experiments of check tests.

Experiment	Revolutions of Anemometer	Time (minutes)	Reading of meter in cu. ft. = v	Time (minutes)	Area under curve (minute velocity) = a	Time = t	Gain in wt. of tube (grammes) = w	$\frac{w}{v}$	$\frac{a}{t}$
IV	38	41	15	46	(3)	40.	0.0014	0.000093	0.0750
V	34	41	9.8	46	2.51	40.25	0.0057	0.00058	0.0624
VI	38	47	0.4	47	2.85	41.75	0.0091	0.023	0.0633
VIII, IX, X, XI	56.5	52	4.36	105	11.66	55.0	0.0088	0.0020	0.212

Discussion of data.

Upon examination of the preceding data of the comparative tests, it is seen that the results are not as satisfactory as could be wished, however, there are many conditions to be considered in judging the results. In the first place, the observations were taken under very trying conditions, indeed, it may be said that the conditions were as bad as could have been selected. For, so much time elapsed between the successive puffs of smoke, that the eye became very fatigued from looking at the bright sky, and when a puff of smoke did come, the matching could not be expected

to be very accurate. This difficulty was further increased by the short time in which the matching had to be performed, and for the same reason, the eye had no time to recover.
From the tabulated data and results, it is seen that in two runs, the area per units velocity varies by as much as twenty percent, however, one of the runs, namely VII, can be accounted for, because the wind was so strong that the hoods could not be used in this run, so the matching was not expected to be very accurate. In the other runs, the area per unit velocity varies, at the most by ten percent, and in one case by as little as one percent, the

last being under good conditions. It appears from this, that under favorable conditions of weather, and with a fair amount of smoke, good results could be effected, what accuracy could be guaranteed, can not be said, but further experiment would probably show this.

It was thought, when the comparison of the gravimetric and the matchuacy methods was proposed, that even though the methods were applied simultaneously to the same chimney, it was necessary to know the velocity of the flue gases. That this is not necessary, can be shown as follows:-
suppose a continuous sample of flue gas of volume V. is drawn

from the chimney, at a point where it's area is A, and during the time t. Let W be the weight of the solid particles contained in that volume, and let x be the mean velocity of the gases passing up the stacks. Then the total volume of gases passing up the stack is Ax, and the weight of solid matter in the same is $\frac{Ax}{V} \times W$ (1)

Suppose the weight w, of particles in a cube of units dimensions of gas appears to have the density d, and the chimney emits a column of smoke of thickness $T = c\sqrt{A'}$, c being a constant depending upon the cross-section of the chimney and A' the area of the stack at the top. Also, let D be the density at the top.

$$\frac{\Pi}{c\sqrt{A'}} = \text{density of a column of smoke of a unit length.}$$

(2) $A x \cdot \frac{\Pi}{c\sqrt{A'}} \cdot \frac{w}{d} =$ total weight of particles ~~that~~ pass out in time t.

Now note the ratio between (1) and (2):–

$$\frac{A x}{V} \cdot W : A x \cdot \frac{\Pi}{c\sqrt{A'}} \cdot \frac{w}{d} = \frac{W}{V} : \frac{\Pi}{c\sqrt{A'}} \cdot \frac{w}{d}$$

which latter is independent of x.

Upon examination of the data for the check tests, in which the gravimetric method was used, it is seen that the results are of no value as a check, but this is easily explained, by the fact that the moisture was probably not entirely removed from the asbestos before the first run with each tube. After this run however, the weight of the solid matter obtained is probably accurate enough; but, there were not enough tests made under this condition, to render comparison possible. Undoubtedly, the method is a good one and should give very good results when it can be applied at a point sufficiently high in the chimney. Experiment alone can show if it would be accurate, when applied at the uptake, or near the base of the stack

is OK in uptake R.J.,

In conclusion, we would recommend further experimental investigation of the various methods suggested, as we feel that discussion alone cannot show the superiority of any one of them. We are confident however, that the method of matching will give results approximately correct; and if any scheme can be devised, by which the eye can be protected from the bright light of the sky while no smoke is being emitted from the chimney, the accuracy will undoubtedly be improved.

Area = 2.64 sq. in.

A = 1.38
l = 0.78

A = 0.78
l = 0.57

A = 0.43
l = 0.47

A = 0.06
l = 0.19

s

f

3 4 1

Total length = 32.0

A. II. 5-18-'98

2

s = 9-50-50
f = 10-21-45
2 Revs. +

98.

A = 1.00
2 = 0.41

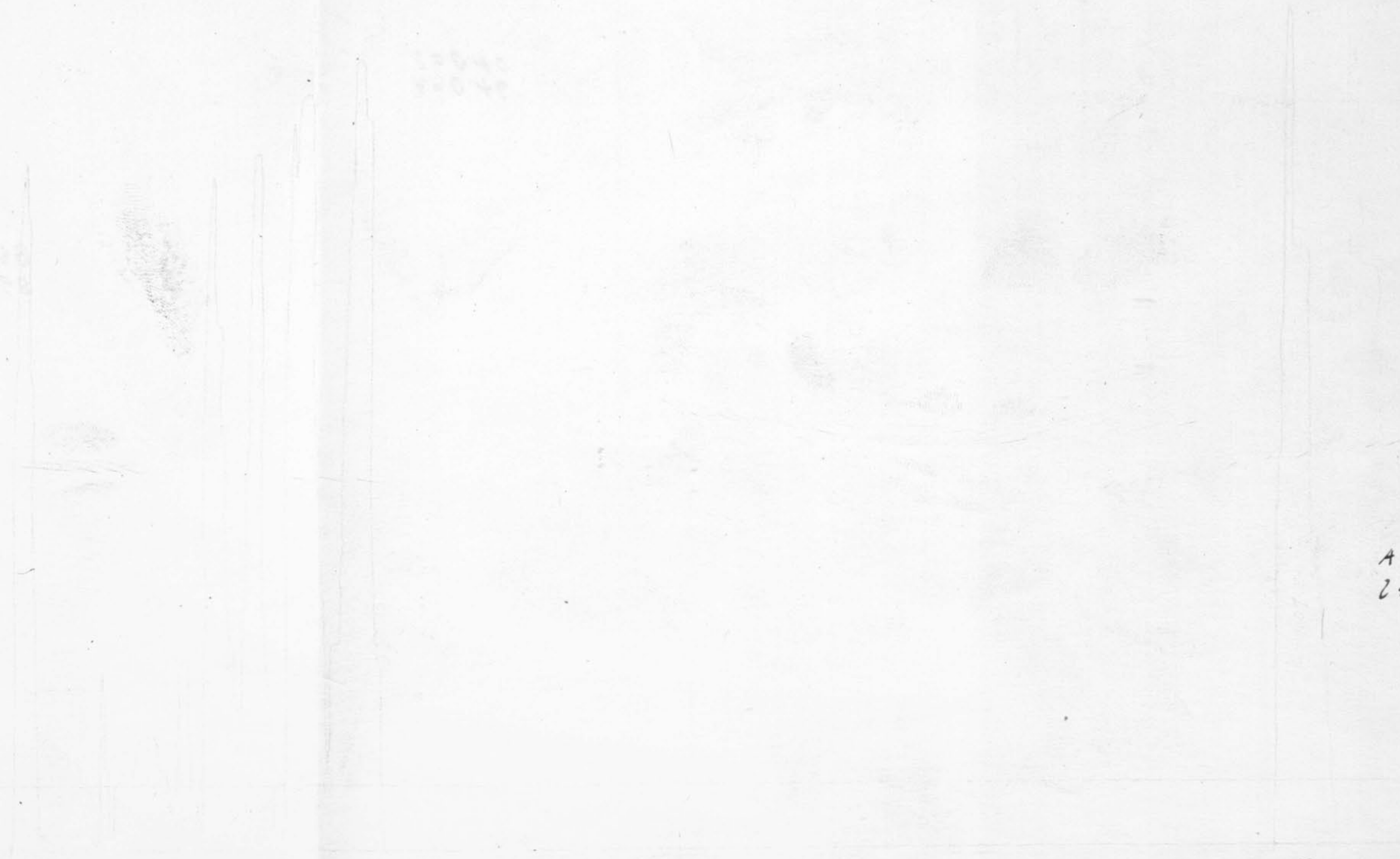
Total Length = 13.98

2

A. I. 5-18-98.

S = 9-15-0
f = 9-28-0

TL = 13.98



A = 1.07
l = 0.41

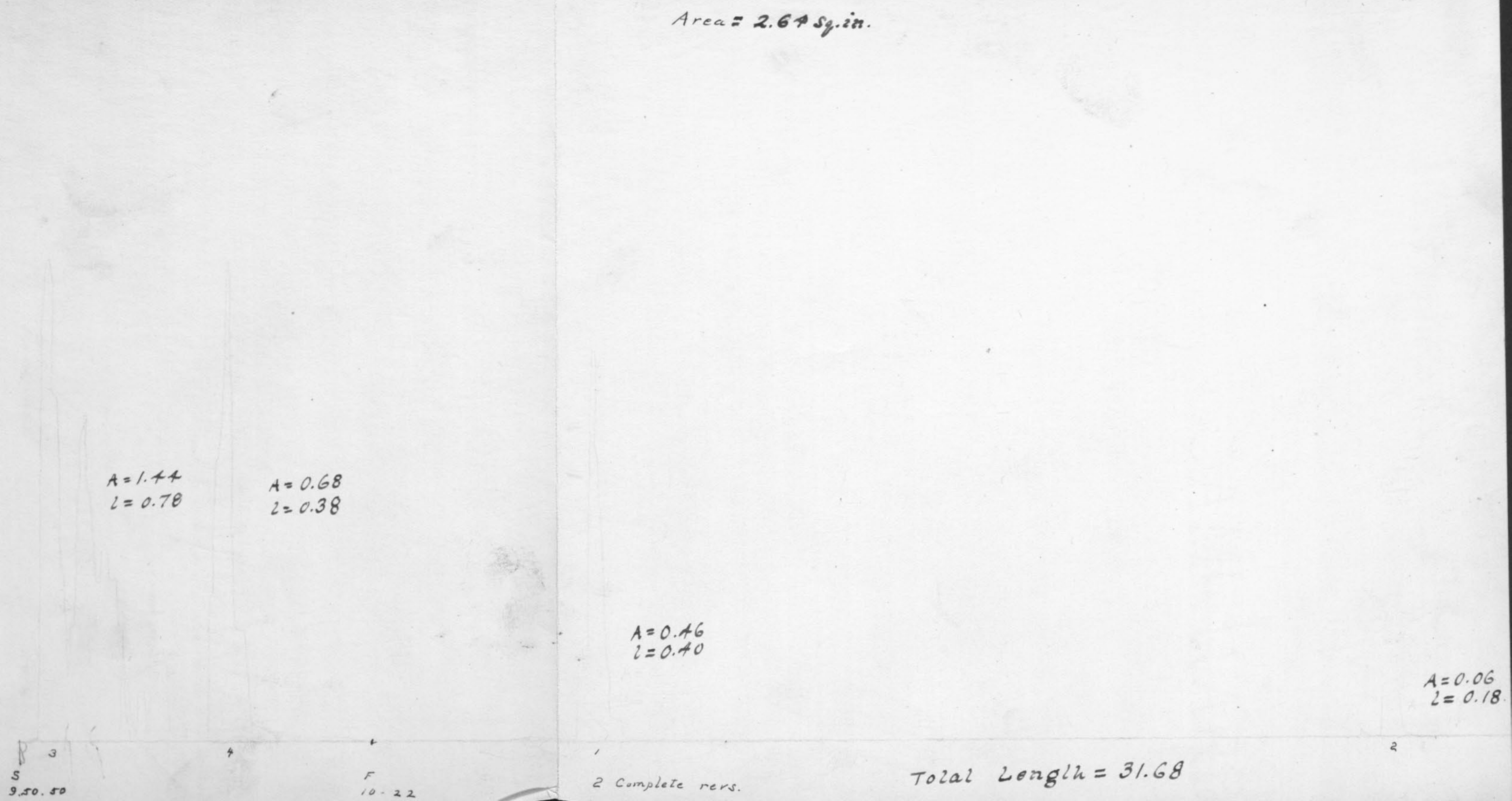
F S
928 9.15

1.

Total Length = 14.34

2

B I
5 - 18 - 98


Area = 2.64 sq. in.
A = 1.44
l = 0.78
A = 0.68
l = 0.38
A = 0.46
l = 0.40
A = 0.06
l = 0.18
3
4
1
2
S
9.50.50
F
10 - 22
2 Complete revs.
Total Length = 31.68

A = 1.92
L = 1.63

A = 0.30
L = 0.31

1.

2

A. # 3.

5-18-48

S = 10-53-0
f = 11-6-20

3

Total Length = 13.61

67

A = 2.10
l = 1.42

A = 0.36
l = 0.24

E
10.53

1.

2.

3

F
11.06

5-18-'38
B III

Total Length = 14.15

Total Length = 40.89

A IV.

5-18-98.

S = 3-7-0

f = 3-50-15.

S

3.07

Total Length = 42.82

F 3-47

B IV

90.

A = 1.04
l = 1.14

A = 0.61
l = 0.70

A = 1.26
l = 2.23

1.

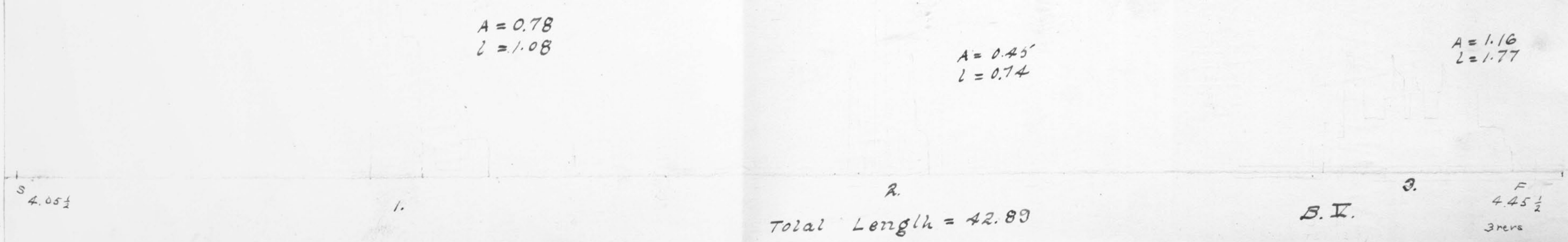
2.
Total Length = 41.25

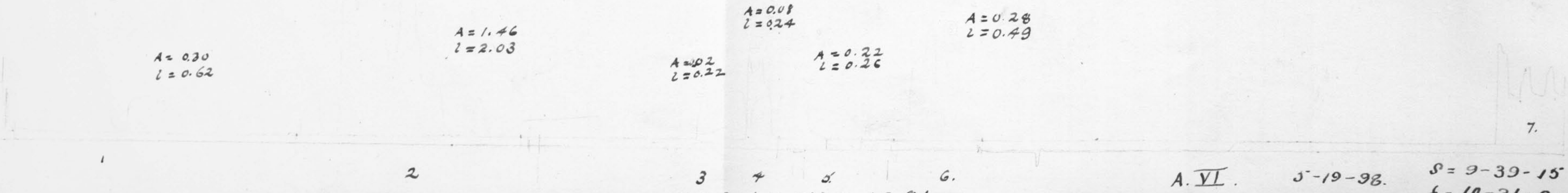
A.V.

3
5-18-98.

S = 4-5-0
f = 4-45-30

91


A = 0.78
l = 1.08
A = 0.45
l = 0.74
A = 1.16
l = 1.77
S
4.05½
1.
2.
3.
F
4.45½
3 revs
Total Length = 42.89
B. V.



Total Length = 42.81

A. VI. 5-19-98.

S = 9-39-15
f = 10-21-0.

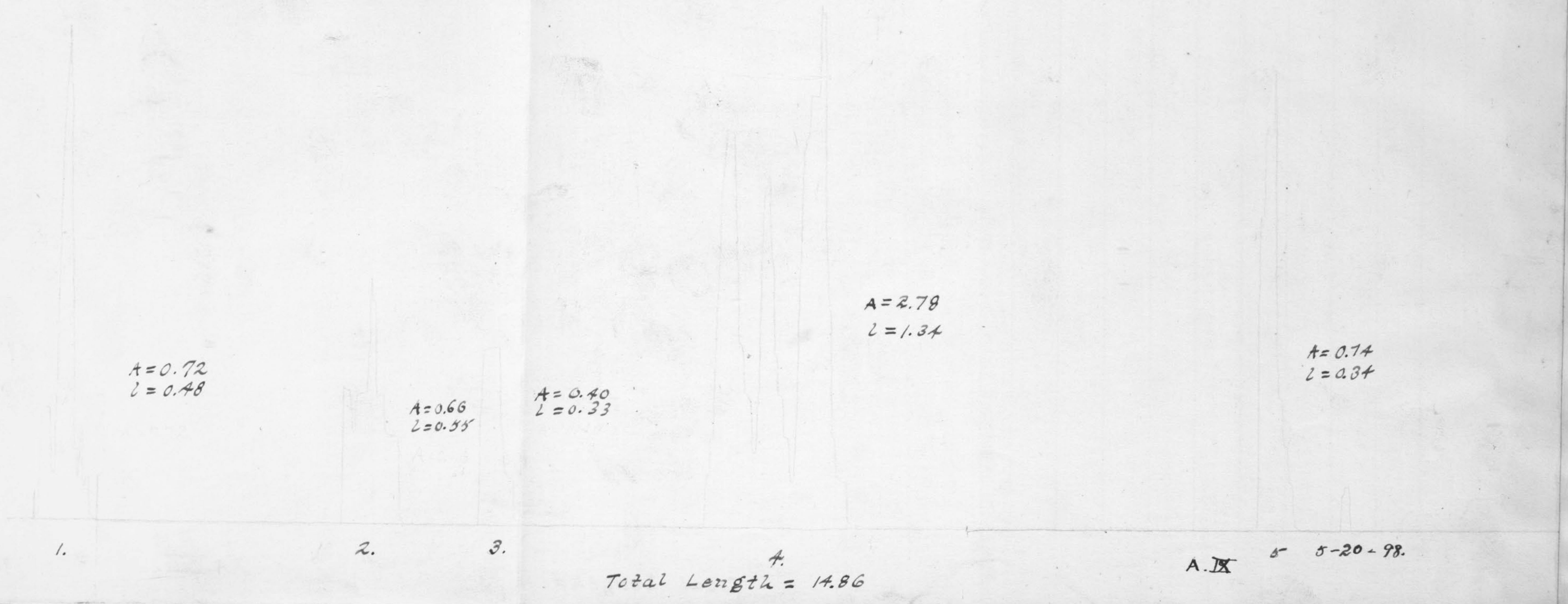
1. 2. 3.

Total Length = 13.50

A VII

5-10-98
S = 3-40
S = 3-54

Total Length = 13.95


A = 0.72
l = 0.48
A = 0.66
l = 0.55
A = 0.40
l = 0.33
A = 2.78
l = 1.34
A = 0.74
l = 0.34
1.
2.
3.
4.
5
Total Length = 14.86
A. IX
5-20-98.

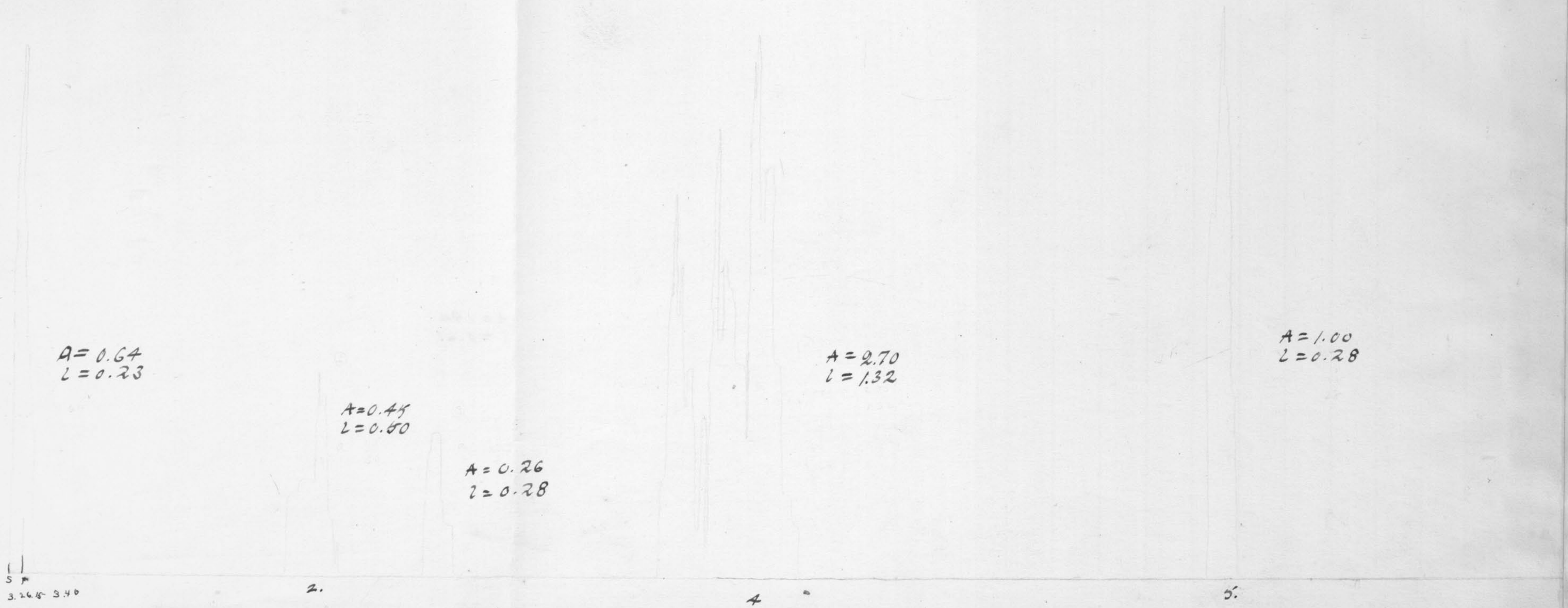
A = 2.36
l = 0.70

Total Length = 11.53

A VIII.

5-20-98

S = 3.05
f = 3.16



B IX

Total Length = 14.49

A = 1.94
l = 0.61

Total Length = 11.34

B VIII

5-20-98