

AN APPARATUS FOR STUDYING COMBUSTION IN A
LAMINAR MIXING ZONE

by

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ABSTRACT

Background material of how this problem arises in bluff body flame stabilization in rocket engines is presented. References are given for the previous theoretical and experimental work performed in this field.

A preliminary testing apparatus is described which was used to investigate the variables of an experimental apparatus for studying combustion in a laminar mixing zone. The results of this preliminary testing apparatus were used to design and build a final apparatus.

The final apparatus has an outer hot stream and an inner cold stream. The enclosure is made mainly of firebrick, ceramic burners, and a castable refractory, Kaocast. The hot stream is hot combustion products that are produced in twenty burners. The stream is mixed with diluent and passed through flow straighteners and a converging section. The cold stream is combustible gases that are also passed through flow straighteners and a converging section. These two streams mix at a very thin section and proceed up through a pyrex tube for observing the resulting combustion.

Thesis Supervisor: A. R. Rogowski

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FOREWORD

The work described in this thesis commenced in the fall term of 1958 when Professor T. Y. Toong suggested the topic to the author. Actual testing was not started until January, 1959. Due to Professor Toong's leave of absence, it was begun under the guidance of Professor A. R. Rogowski. All work was done in the Sloan Automotive Laboratory.

Financial support was obtained from the Research Grant of the Shell Oil Company for the materials in the apparatus and from Detroit Diesel Engine Division of the General Motors Corporation for my time involved in this project.

Throughout the research, Professor Rogowski and T. N. Chen constantly provided professional guidance and moral support. Much valuable help came from Professor C. F. Taylor, Mr. J. Caloggero, Mr. P. McGovern, and Mr. E. Gugger.

The author wishes to thank all those who assisted in any way during the thesis project, especially his wife, Jean, for her typing and indulgence. It is hoped that this apparatus will become a worthy addition to the many combustion research projects of the Sloan Laboratories.

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I. INTRODUCTION

The study of combustion in a laminar mixing zone was initiated from the combustion problems in thermal jet propulsion systems. Previously, theoretical and some experimental work has been performed on combustion in mixing zones by studying the characteristics of the mixing of hot combustion products with cold combustible gases.

The specific problems of this thesis were to determine the variables connected with the testing of an apparatus to study combustion in a laminar mixing zone and to use these results to design a more complete apparatus to be operated over a wide range of conditions.

The general procedure followed in this investigation included: research into past theoretical and experimental work, building and testing a preliminary apparatus, designing a final apparatus, and partially building this final apparatus.

It is the two-fold purpose of this thesis to present the results of the preliminary testing apparatus and to present the design of a new apparatus to study combustion in a laminar mixing zone.

The organization of the thesis will follow the exact sequence of the investigations as follows:

- III Background Material
- IV Preliminary Testing Apparatus
- V Final Apparatus

II. CONCLUSIONS AND RECOMMENDATIONS

The purpose of this section in the thesis is to present the conclusions of the investigation undertaken and to provide recommendations resulting from this investigation. Since the actual conclusion drawn from the investigation is a physical design and a physical apparatus, drawings and photographs will concur with the following conclusions.

General Conclusions:

The following are the general conclusions resulting from the investigation.

1. The experimental work previously performed was not quite as extensive as was felt it could have been and many relationships were not investigated. Thus, further experimental work was undertaken (page 10).
2. Thus, the only possible solution was to design a better, more complete apparatus (page 18).
3. The three sections, Hot Combustion Products Section, Cold Combustible Gases Section and External Sections constitute the final apparatus for studying combustion in a laminar mixing zone (page 39).

Specific Conclusions

The following are the specific conclusions resulting from the investigation arranged by the thesis sections in which they are developed.

Section III

1. The temperature profile of the cold stream could not be controlled due to heating from the hot stream.
2. The velocity profile of the two streams could not be controlled because of turbulence and thick boundary layers
3. The hot stream temperature could not be held uniform or controlled.

Section IV

Hot Products Section Data

Bottom Enclosure

over-all size	3' x 3'
center hole	2" diameter
material	firebrick

Top Enclosure

outside diameter	$30\frac{1}{4}"$
height	$4\frac{1}{4}"$
center diameter	5.625"
flow curvature	cubic
material	steel - Kaocast

Center Enclosure

tip diameter	17"
hub diameter	2.5"
hole diameter	2"
height	6.9"
material	Kaocast

Burners

number	20
size	3-1/16" x 3-1/16" x 5-13/32"
make	Selas KZ-552-SN3

Dilutent

size	1/2" diameter
material	stainless steel tubes

Flow Straighteners

size per piece	3" x 1-1/2" x 7/6"
hole diameter	1/8"
holes per piece	55
number of pieces	43
material	Alsimag 222

Cold Combustible Gases Section Data

Straightening and Calming Section

outside diameter	5.5"
inside diameter	4.04" to 1.5"
flow curvature	cubic
material	aluminum
tube size	1/8" diameter, .014" wall 5" long
number of tubes	880
tube material	brass

Center Tube

length	9.6"
o.d.	2"
i.d.	1.5"
flow curvature	cubic
material	alundum

External Sections Data

Observation Section

o.d.	6"
i.d.	5.625"
length	3"
material	pyrex

Chimney

size	6"
material	sheet metal

Recommendations

The following recommendations are offered to complete construction of the apparatus and to complete the investigation of combustion in a laminar mixing zone.

1. Complete the machining and construction of the sections shown in the final design.
2. Complete the piping and metering necessary for the air, fuel, and diluent.
3. Run preliminary tests on velocity and temperature profiles over the desired flow range.

4. Investigate combustion and ignition in a laminar mixing zone by correlating detachment distances with velocities, fuel-air ratios, temperatures, and fuels.

III. BACKGROUND MATERIAL

The problem of ignition and combustion in a laminar mixing zone is a physical problem to which much recent research has been devoted. Two of the main situations associated with this problem are thermal jet propulsion systems and rocket motors. Specifically this problem arises in a ram jet combustion chamber where bluff bodies are used to provide a relatively stagnant region in which a pilot flame can stabilize. The bluff body is required because the mixture velocity is much greater than the burning velocity. When using a bluff body flame stabilizer, only a portion of the combustible mixture is passed into the stagnant region and is burned as follows:

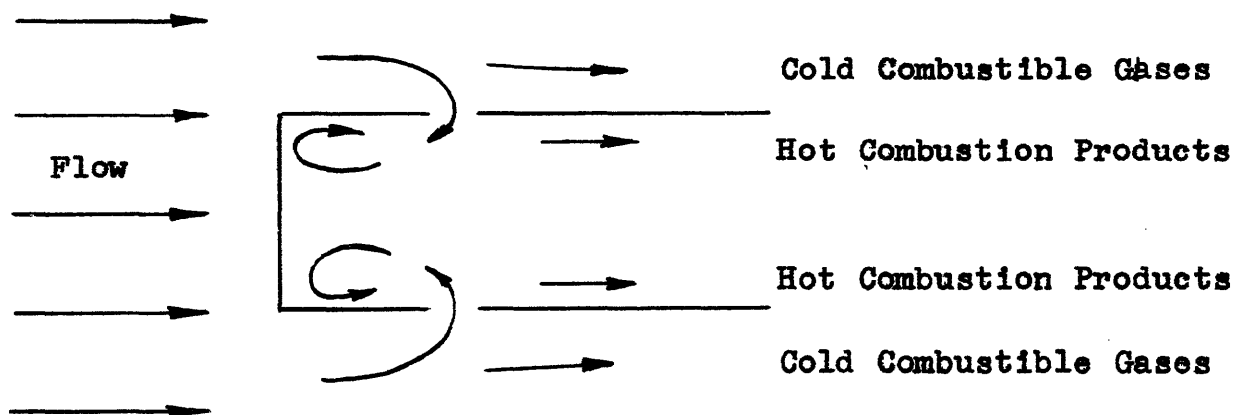


Figure I. Bluff Body Flame Stabilizer

When the hot and cold gases pass out of the bluff body there is an interaction between the hot combustion products and the cold combustible gases.

This interaction consists of chemical reactions, momentum transfer, heat transfer and mass transfer at the boundary of the hot and cold streams. These interactions initiate another flame which may then propagate throughout the cold mixture and complete combustion. These interactions, and the reason why hot gases cooler than the adiabatic flame temperature of the cold mixture can cause a flame to be initiated, are shown in the following diagram.

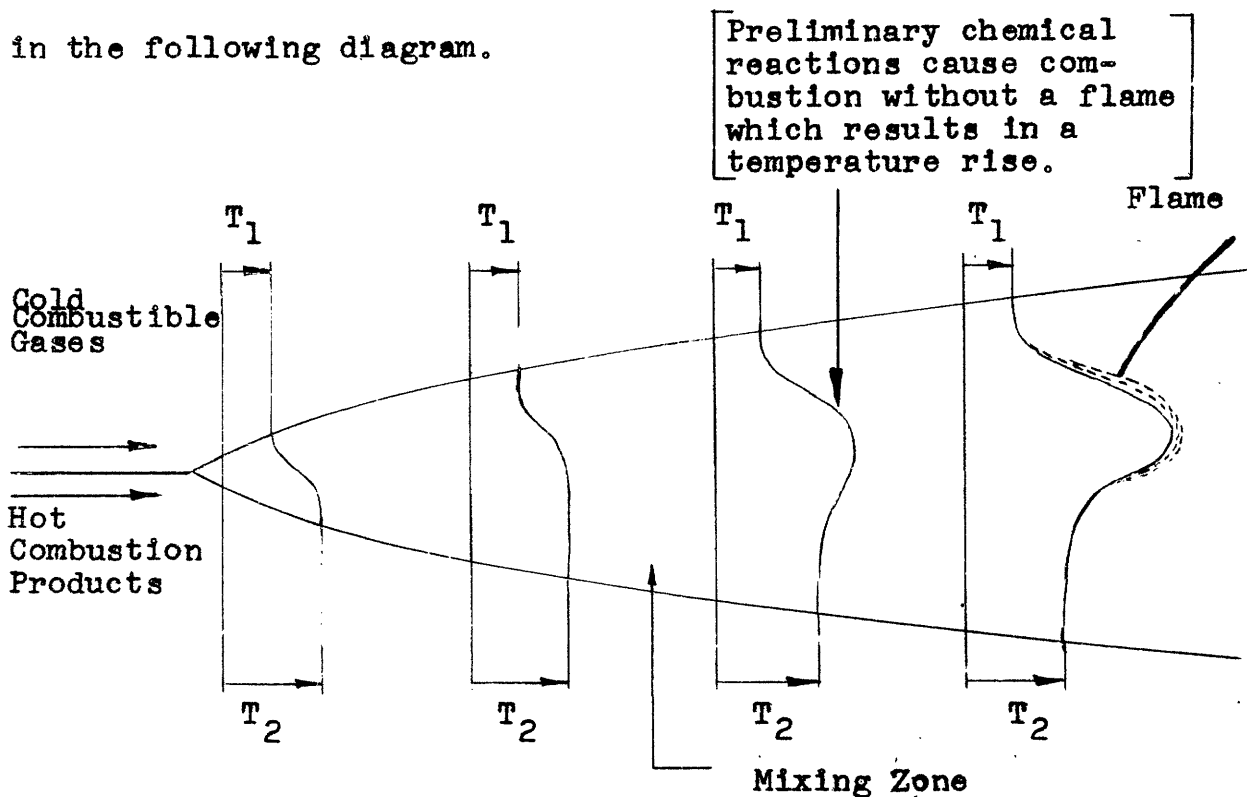


Figure II. Schematic of Flame Initiation . . .

There have been investigations simulating this process with a hot stream of gases mixing with a cold stream at some boundary. Marble and Adamson¹ were one of the first to take a theoretical approach to the problem. They made their analysis for one stream of cool combustible mixture, and the second of hot combustion products with uniform initial velocity profiles. They used the boundary layer integral technique, introduced by Kármán, to make simplifications.

After Marble and Adamson did their analysis, others refined it. S. I. Cheng and A. A. Kovitz² did theoretical work on "Ignition in the Laminar Wake of a Flat Plate" and used Blasius profiles as initial velocity distributions. This was done as an improvement over Marble and Adamson's uniform profiles. S. I. Pai³ did his theoretical work on "Laminar Jet Mixing of Two Compressible Fluids with Heat Release". He made a general analysis, and then simplified it for several specific cases. One specific case included Marble and Adamson's uniform profile considerations. The only experimental work performed was by F. H. Wright and J. L. Becker⁴ on "Combustion in the Mixing Zone Between Two Parallel Streams". The equipment consisted of a cylindrical apparatus with an inner hot stream, heated by exhaust gases from a turbujet can burner, and an outer cold stream. Their results included correlations between the detachment distance of the flame from the point where the two streams mixed to

equivalence ratio* and hot stream temperature for various stream velocities.

The investigations made by the above men are the bulk of the theoretical and experimental work that has been done in this field. The experimental work previously performed was not quite as extensive as was felt it could have been and many relationships were not investigated. Thus, further experimental work was undertaken.

*fuel-air ratio/stoichiometric fuel-air ratio

IV. PRELIMINARY TESTING APPARATUS

The experimental investigations made by Wright and Becker were not completely satisfactory and further experimental work was desired. Following the recommendations of a paper by C. W. Haldeman (term paper for T. Y. Toong, 1958) a preliminary testing apparatus was built to determine the problems that would be encountered in an apparatus of this kind and to determine if a flame could be initiated.

One of the basic differences of this apparatus from the one Wright and Becker used was the hot stream was the outer stream and the cold stream was the inner stream. The reason for this is illustrated by Figure II. It can be seen that if another hot stream is added above the one shown, as in a pipe, then the two flames initiated will meet and produce a flame similar to a bunsen burner flame.

Hot Combustion Products Section

Hot gases were produced with four bunsen burners by burning a mixture of air and natural gas. A baffle and screen were used above the burning gases to mix and smooth the flow. It was found immediately that the hot gases that approached the mixing section were not of uniform temperature. Thus, a gas range burner was incorporated since it was uniformly circular and had a hole in the center for central cold stream tube. The flow capacity of the burner was increased by symmetrically drilling more holes in the burner face.

The burner was supplied with air from a large centrifugal pump that was metered by an orifice. The fuel was natural gas from the gas main, and it was metered by a calibrated rotometer. Valving was provided to adjust either air or fuel flow (see Figure III). The hot stream was always operated at a stoichiometric fuel-air ratio (15:1) (see Appendix, Section A) because it was not desirable to have excess air or fuel in the hot stream to interact with the cold stream.

In order to stabilize the flame producing the hot gases, a stainless steel wall was inserted around the burner (see Figure IV). This wall helped stabilize the flame by the vortex motion of the gases along the wall. The stainless steel wall was sealed to the burner with refractory clay to prevent diluting or radical leakage.

A screen was used further upstream to allow a five-inch section for the large scale turbulence to mix the gases (see Figure IV). The screen also served to break up the boundary layer. The stainless steel screen would then smooth the flow and convert the large scale turbulence to small scale turbulence just before mixing.

Cold Combustible Gases Section

The cold gases were introduced into the apparatus by a pipe that entered through the center of the hot burner and ascended above it approximately eight inches. The pipe was cast iron, 5/8" diameter, that was ground to a sharp edge

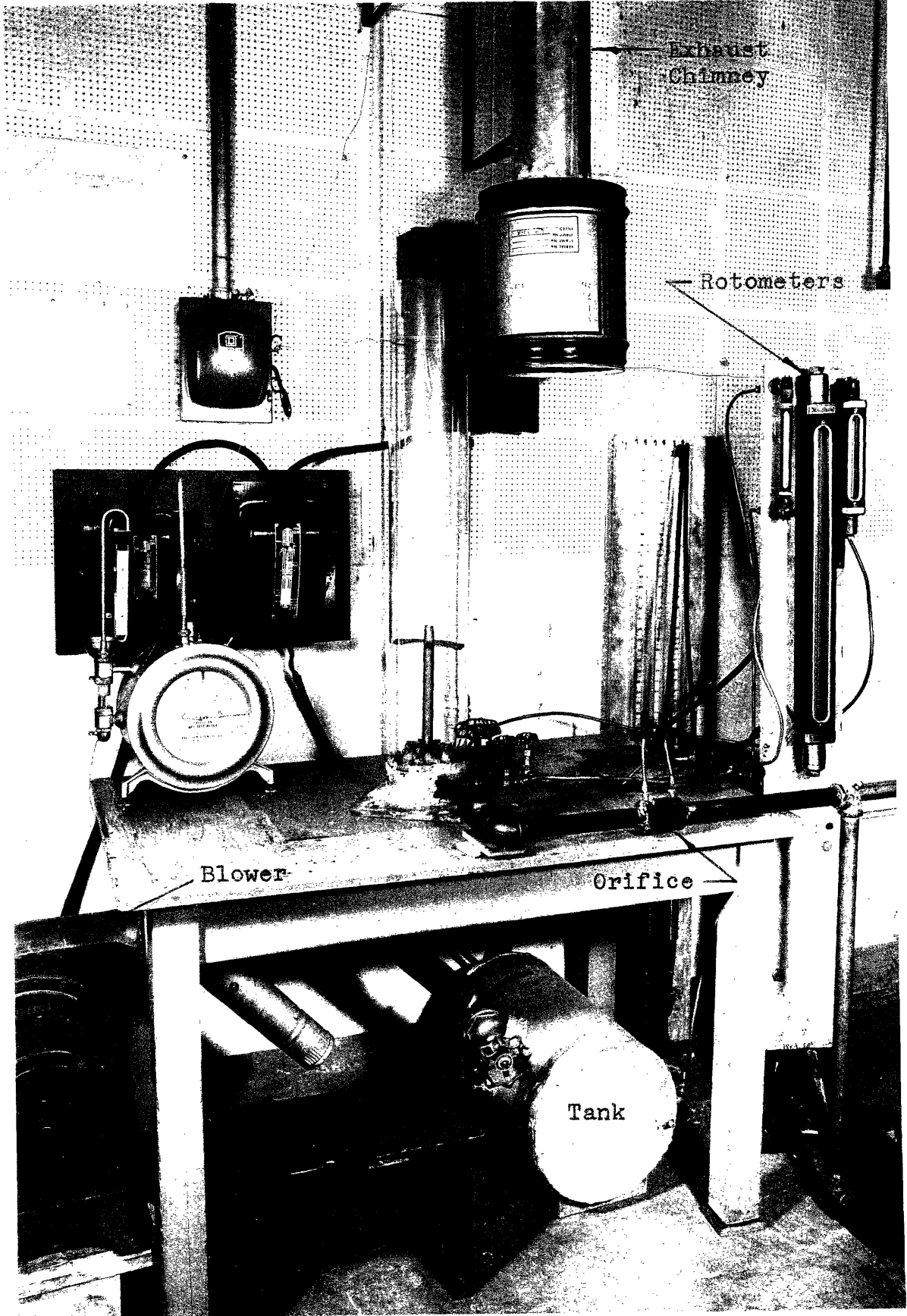


FIGURE III PRELIMINARY TESTING APPARATUS

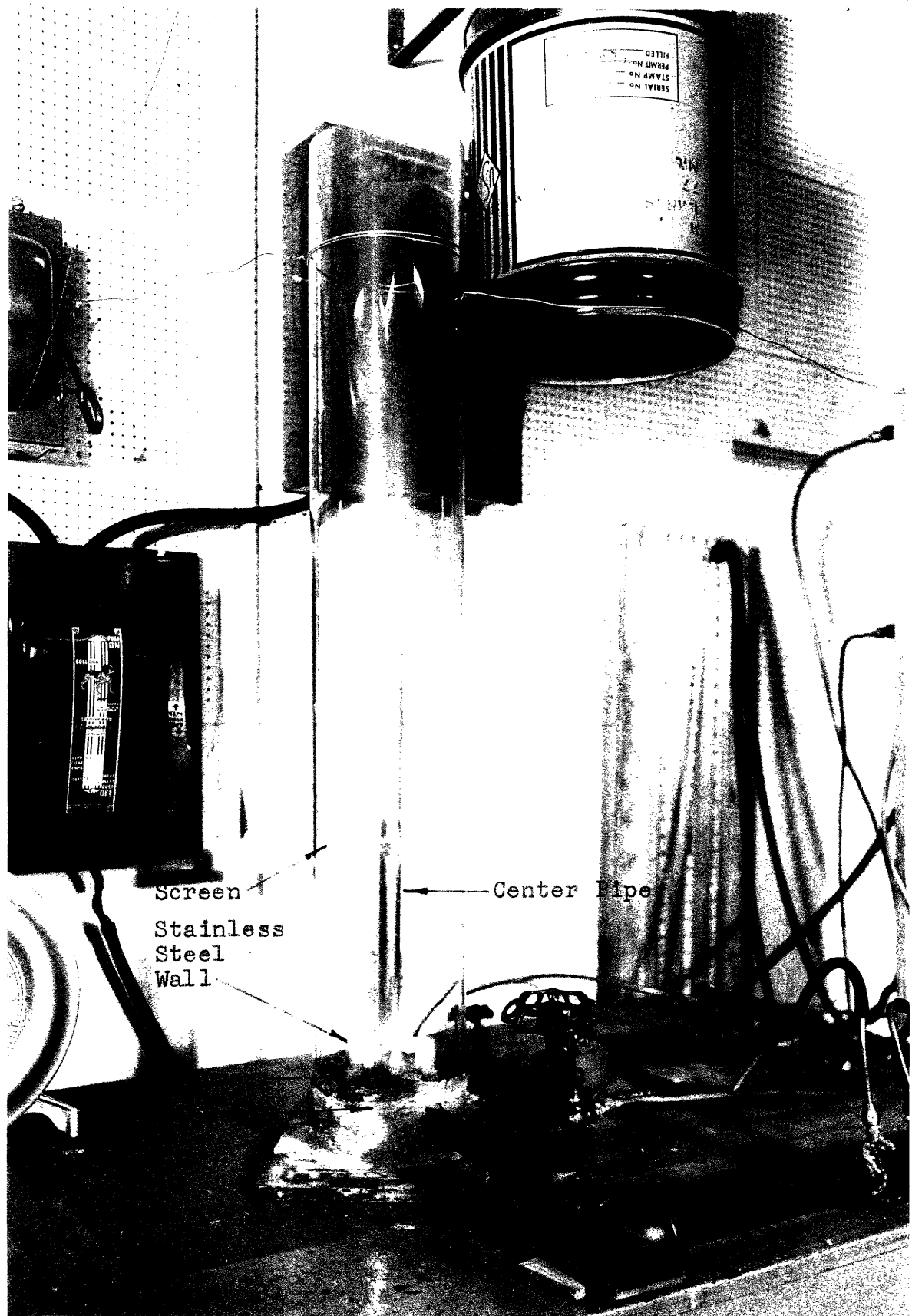


FIGURE IV TEST SECTION OF PRELIMINARY TESTING APPARATUS

at the top to facilitate mixing at a minimum thickness. The sharp edge allowed mixing with small scale eddies.

The cold gases consisted of an air and fuel mixture at room temperature. The air was supplied by a small blower shown under the table in Figure III. The fluctuations in the flow were smoothed by passing the flow into a tank and then tapping off the tank. The air was metered by a rotometer, passed through a valve, and then mixed with fuel. Again the fuel was natural gas from the main, and it was metered by a small rotometer. The rotometers for the air and fuel were calibrated with the wet test meter shown in Figure III.

The mixture of fuel and air was introduced through the center pipe at a velocity equal to the hot stream velocity. Since the mixture was combustible a flame could be initiated. The flame could stabilize, flash-back or blow-off. If it stabilizes or blows-off there is no problem, but if it flashes back, it could flash back down the center pipe, because the top of the pipe is ground to a sharp edge and it will not act as a flame holder. Thus, the flame in an enclosure containing a combustible mixture could cause an explosion. In order to prevent this, a quenching screen was inserted inside the center pipe approximately one inch below the mixing point.

External Sections

The apparatus was situated on a table shown in Figure III. The build up then consisted of a flat refractory plate, a sheet metal section and pyrex tube, six inches in diameter and three feet long. The sheet metal section allowed the pipes to be entered through the wall and the pyrex tube allowed visual observation of the flames. All joining sections were sealed from air leakage by a clay material. This was necessary since an exact fuel-air mixture was required.

An exhaust chimney was built out of six-inch diameter, three-foot long, sheet metal tubing section with a can welded to the end (see Figure III). The chimney passed through the ceiling to the outside.

Experimental Procedure and Results

Experimental testing was performed on this preliminary apparatus in a trial and error manner since its function was to disclose the variables connected with an apparatus of this kind. Testing consisted of lighting the hot stream burner, varying the fuel-air ratio of the cold stream and varying the velocity of both streams. As stated previously, the hot stream was always operated at a stoichiometric fuel-air ratio. The procedure for testing was to light the hot stream burner, turn on the air and fuel to the center burner and wait for a flame to be initiated. The temperature of the hot and cold

streams were in the range of 1500°F and 100°F respectively. The temperatures were measured with a shielded thermocouple that was suspended in the streams. The velocities ranged from five feet per second to two feet per second. The low values of velocity were due to the limited flow through the hot burner without causing blow-off.

One of the first deficiencies found in this apparatus was the heating of the cold stream pipe. The hot gases were passing over almost the full length of the pipe and after considerable operating the center pipe would be red-hot. This meant that the temperature profile of the cold stream was hardly uniform and was constantly varying as operation continued. This information did prove to be useful in later work.

There were flames initiated with this apparatus but none were very conclusive. After operating for short periods of time, it was found that if the fuel to the hot stream burner was shut off, a flame would be initiated at the top of the center pipe. This flame seemed to stabilize on the top of the center pipe even though the pipe was ground to a sharp edge. If the cold stream velocity were high enough, at times the flame would blow-off. Still many other times there would be no flame initiated at all. Of course all this information was obtained in the transient condition of turning off the fuel to the hot stream burner. These same results could never be acquired under steady state conditions.

The temperature of the cold stream was one variable not changed except for the heating in the boundary layer of the cold stream. This was investigated by starting under the normal conditions and allowing the center pipe to be heated. This meant that the cold stream was being heated, but still no resulting flame was observed.

Many other trial and error procedures were investigated and only under transient conditions could any of the three conditions of flames be found ie: blow-off, flash-back, or a stabilized flame on the center pipe. The limitations of velocity and temperature profile were the greatest problems. The velocity could not be increased appreciably since there was not enough space for additional burners. The temperature profile of the cold stream could not be controlled because if the pipe were wrapped with a cooling coil, the streams could not mix at a thin section. Then there were many small problems that could not be solved with the preliminary apparatus such as the following: straightening the flow for both the hot and cold stream, striving for a uniform velocity and temperature profile and adding diluent to control the hot stream temperature. Thus, with the above results in mind, the only possible solution was to design a better, more complete apparatus.

V. FINAL APPARATUS

The preliminary testing apparatus performed a portion of its function, which was to initiate a flame or divulge information for another design. The apparatus achieved the latter of these two, and ideas for a final design were taken from the results. Different designs were considered, all of which had an inner cold stream and outer hot stream for previously discussed reasons. Essentially the following factors were included in each design: insulation of the cold stream from the hot stream, provisions made to have uniform velocity, and temperature distributions and provision for larger flows with diluent. Basically the designs under consideration differed only in the means by which the hot gases were introduced. The final design chosen consists of three sections: Hot Combustion Products Section, Cold Combustible Gases Section, and External Sections (Figures XIII and XIV in Appendix B).

Hot Combustion Products Section

The hot combustion products section is the one in which the hot gases are produced for the mixing zone. This section consists of a bottom enclosure, a top enclosure, a center enclosure, burners, introduction of diluent and flow straighteners.

Bottom Enclosure

The bottom enclosure is shown in Figure V as a fire-brick base. The center of the base has a two-inch diameter



FIGURE V FIREBRICK BASE (BOTTOM ENCLOSURE)

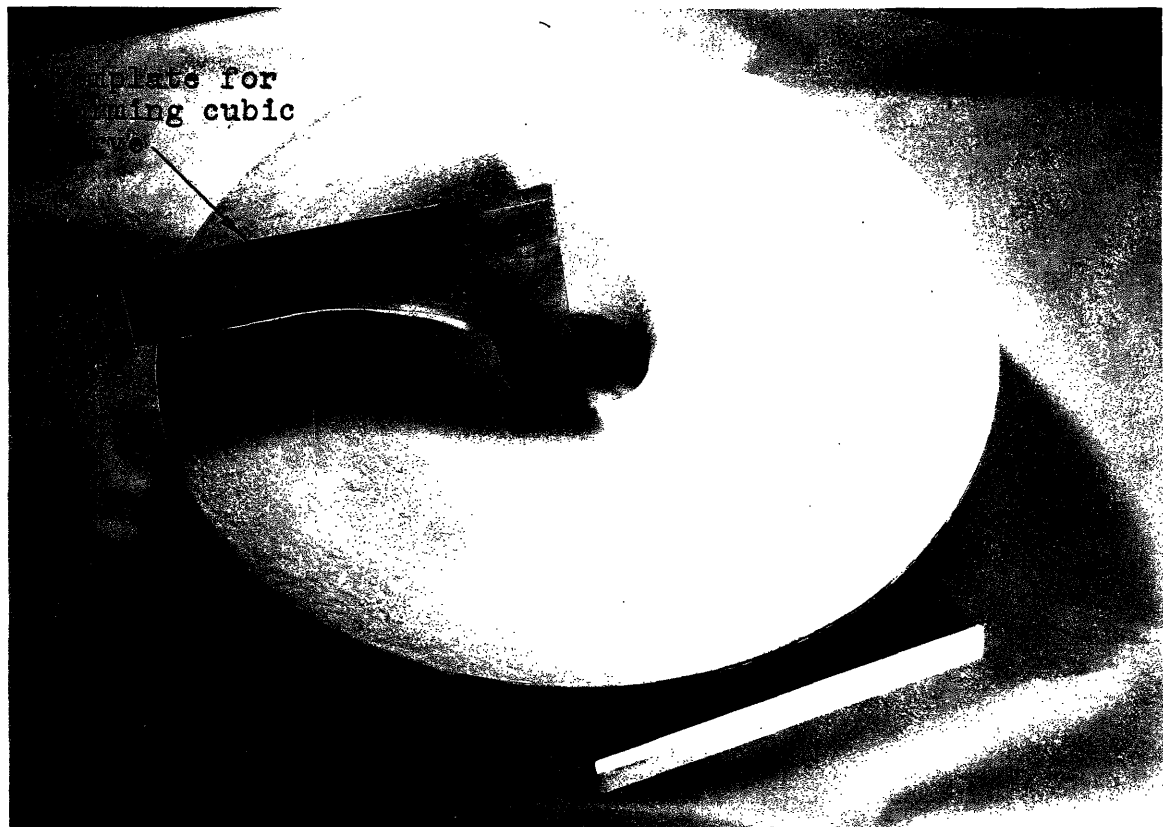


FIGURE VI TOP ENCLOSURE

hole in it, to pass the center tube through, and provisions for connecting the cold combustible gases section.

The firebrick is a K-30 insulating type that will stand service temperatures up to 2900°F in a directly exposed position. The thermal conductivity is low (ranging from .161 btu/hr ft °F at 500°F to .432 btu/hr ft °F at 2500°F) which means less heat loss and higher operating temperatures. The firebrick also has a low heat-storage-capacity so closer and faster temperature control can be obtained.

The bottom enclosure consists of 32 pieces of this type firebrick that are 9" x 4-1/2" x 2-1/2". The bricks are layed on their 9" x 4-1/2" face and cemented together with air-set Babcock and Wilcox mortar that has a temperature range as high as 3000°F. The hole for the center tube was made by filing quarter-circles in the corners of the four center bricks which were then joined together. Bolts (1/4-28 x 2") were mounted through the four bricks so the cold combustible gases section could be joined to the firebrick. Since the heads of the bolts would be covered when the whole apparatus was assembled, the bolt heads, with large washers for support, were recessed in the brick. The bolt heads were then prevented from turning by putting metal strips in the hole along the bolt head flats and filling the hole with air-set mortar. This allows the pieces to be assembled and disassembled with nuts, without holding the bolt heads.

The whole bottom enclosure rests on a piece of transite placed on a table. Both the transite and table have an eight-inch hole in the center to receive the cold combustible gases section.

Top Enclosure

The top enclosure is the top half of the hot products flow path* (Figure VI). Since the flow of hot products must make a 90° angle turn from the horizontal to the vertical, some flow path was necessary. It was decided to use a cubic curve for a path, as in nozzle flow, so there would be no slope or change of slope at the mixing zone. The other end of the curve was smoothed with an 11.58 inch radius so the flow would start out of the straighteners on a smooth curve#.

The top enclosure is partly a piece of reinforced castable, 4" thick, made from Babcock and Wilcox Kaocast. Kaocast can withstand a continuous temperature of 3000°F and will melt at 3200°F. It is made of refractory calcines or grogs blended with a binder. Kaocast will set in air, but full strength is not obtained until firing. The remaining portion of the enclosure is a steel plate 30" in diameter and 1/4" thick with a 5.625" diameter hole bored in the center. The steel plate has a steel band around it that is 4-1/4" high and 1/8" thick.

*The center enclosure and the center tube make up the other half of the flow path.

#See section on Flow Straighteners

The top enclosure was made by welding the band to the plate and filling the bottom of this enclosure with reinforcement. The reinforcement consisted of four pieces of one-inch angle iron welded radially, evenly spaced from the outer edge to within an inch of the center hole. These were used to keep the plate from deflecting and to help reinforce the kaocast. Short pieces of bent welding rod were welded at random to the bottom of the plate, also to act as a reinforcement. The angle iron and the welding rods were then covered with tar and the kaocast was poured in. A sheet steel template was used to form the desired smoothed cubic curve. The tar was utilized because iron has a larger coefficient of expansion than the kaocast and it was feared cracking would occur.

The kaocast was cured for 24 hours. Since a furnace large enough for firing the piece was not available, it was fired by a natural gas burner*, in an enclosure of fire-brick and a piece of transite, to approximately 300°F. Firing is only necessary to alleviate the kaocast of moisture and to strengthen it. The firing must be slow at first, which was obtained by this method, and can be faster at higher temperatures, which will be obtained when in operation. After firing, the curved portion of the enclosure was covered with a very thin layer of air-set mortar, to achieve a

*One of the burners described in the section titled Burners.

smoother surface, and then was sanded to the final shape desired.

Center Enclosure

The center enclosure was designed as a flow path and as a means of insulating the center tube from the hot gases (see Figure VII). Insulation is not entirely available because the streams must mix at a thin section. The center enclosure has an approximate two-inch diameter hole in the center to admit the Alundum tube*. It also has a smoothed cubic curve on the outside. The cubic curve is the same type as on the top enclosure which starts at the mixing point and is smoothed with a 10.00-inch radius at the flow straighteners.

The center enclosure was also cast with kaocast. The top and edges had to be cut off at a quarter-inch thickness because casting is not practical in thin sections. The curve was blended in from the cut-off point with Selas 206G cement.

The castable piece was made in a mold with a core. This mold was a wood base covered with 15 pounds of plasticine (Figure VII). The plasticine was shaped with a sheet metal form. The hole in the center was made by supporting a piece of pipe with an approximate two-inch outside diameter. The

*See Cold Combustible Gases Section

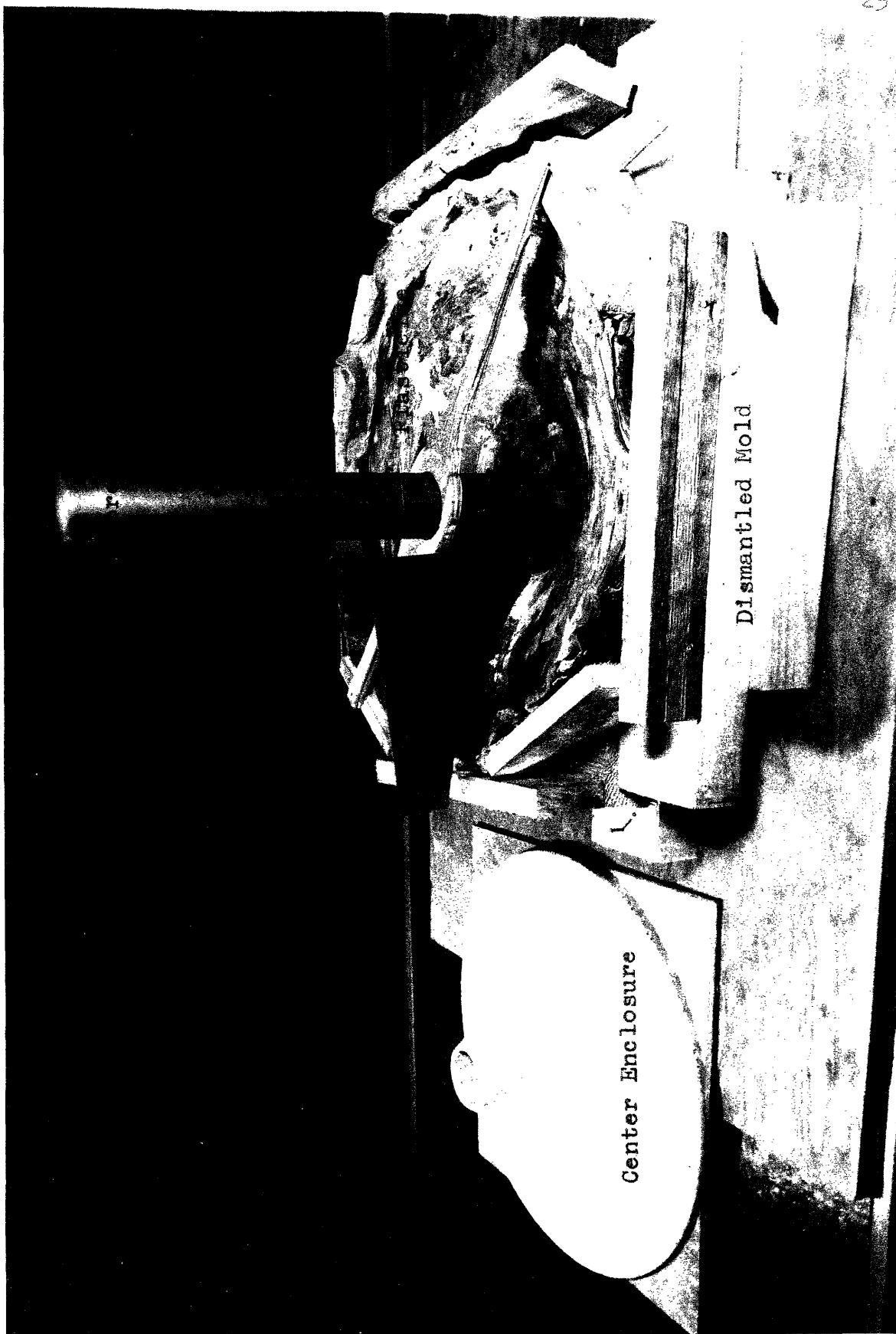


FIGURE VII CENTER ENCLOSURE AND MOLD

plasticine and the pipe were covered with a heavy oil so the kaocast would part. The kaocast was then put in the mold in small quantities and tamped down to insure the best obtainable surface on the flow side. The cast piece did not readily part and the mold had to be partially dismantled. The center enclosure was then allowed to cure for 24 hours before it was fired. The firing was done in the Metallurgical Foundry on the following schedule:

150°F	16 hours
200°F	1 hour
300°F	1 hour
400°F	1 hour
600°F	1 hour
800°F	1 hour
900°F	1/2 hour

After firing the castable was covered with a thin layer of air-set mortar and was sanded to a smooth surface.

Burners

The hot combustion products section was designed without any specific burner in mind. The producing of hot products can be done in many ways so the burners were determined after the flow paths were ascertained. A burner that could stand the high enclosure temperature was needed. Also, one that would operate over a large flow range so that a large velocity range could be obtained.

A burner was found that has these characteristics. It was a Selas KZ-552-SN3 duradiant burner, (Figure VIII). The burner consists of a metal mixture tube with a square

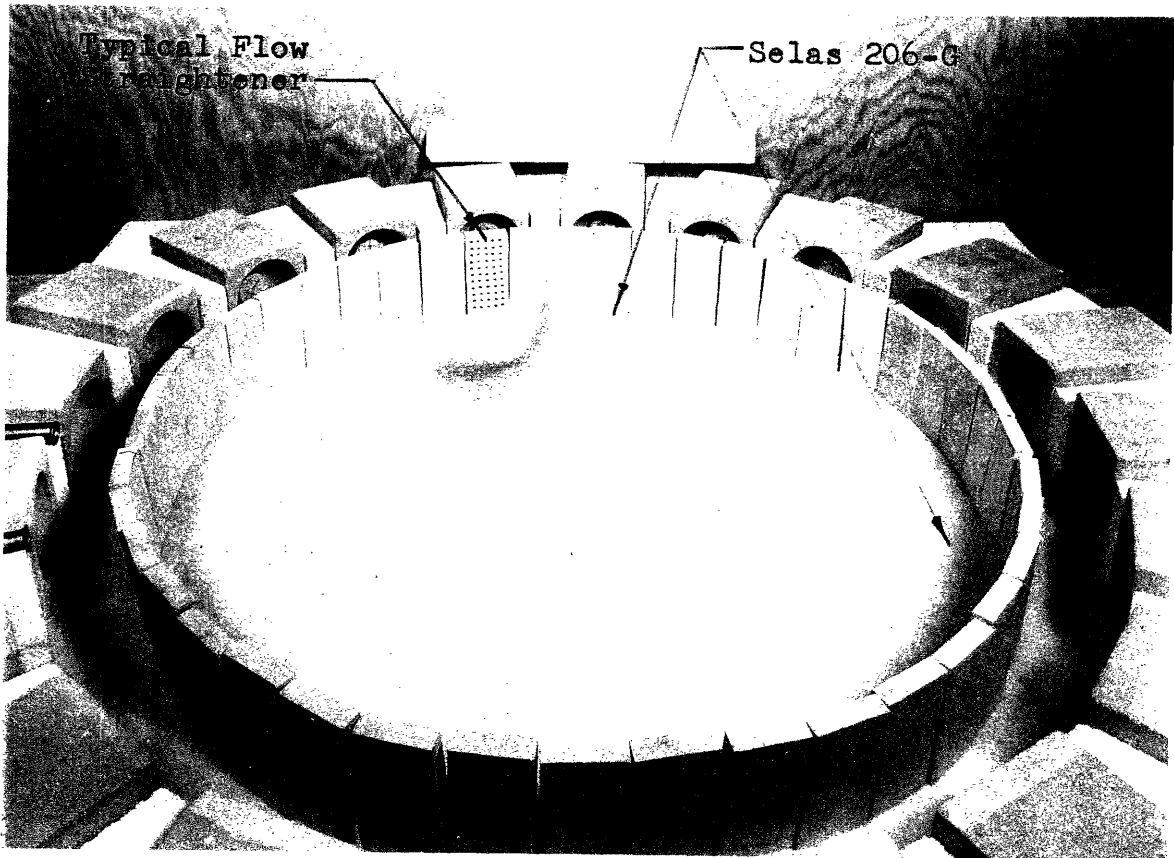
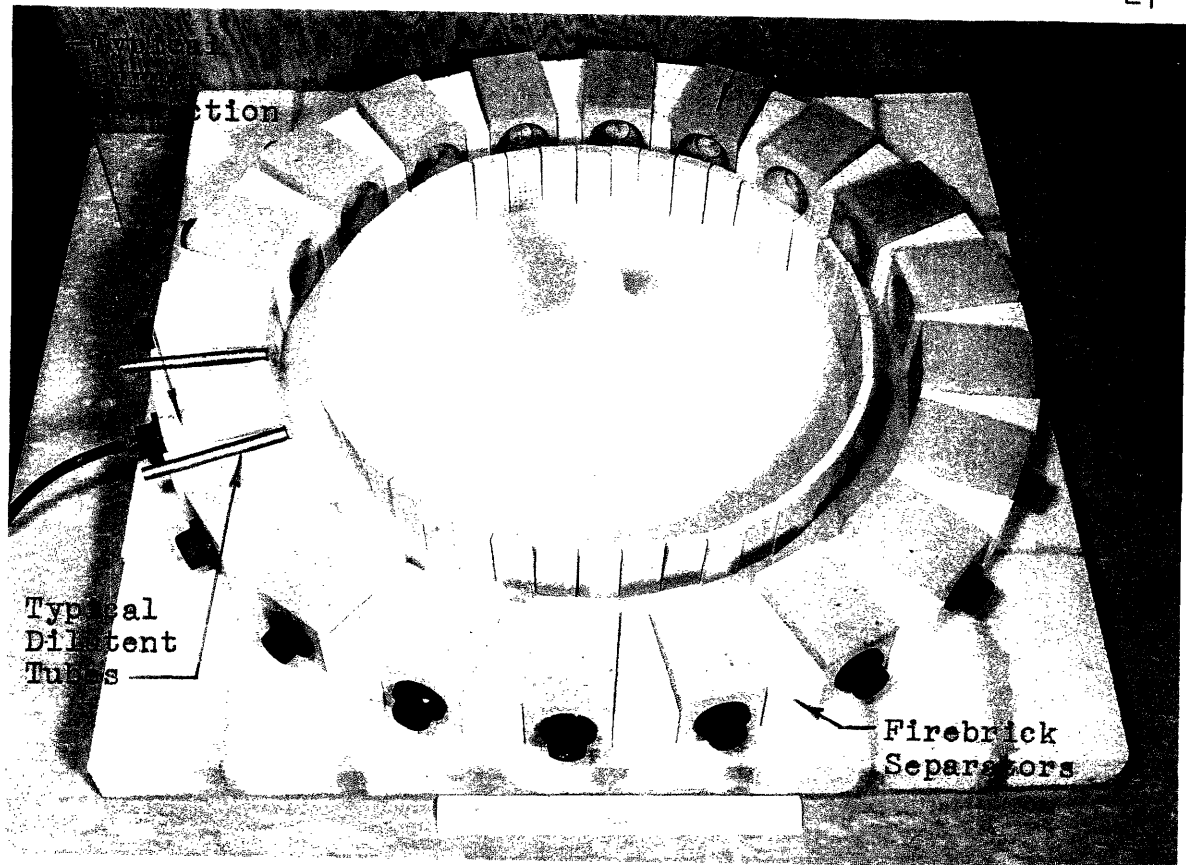


FIGURE VIII FINAL APPARATUS-OPEN POSITION

ceramic housing around it. The burner is designed to operate in an enclosure but on account of the metal mixture tube it will only stand an enclosure temperature of approximately 2500°F. The burning end has a refractory cup-shaped design in it. A molded high temperature ceramic tip is fitted in the cup and screws into the metal mixing tube. The tip has numerous narrow slots molded into its periphery which acts as a distributing head. The radial flow of mixture passes out the tip and is burned within the refractory cup. The inside of the cup is rough and promotes turbulence and thus, completes burning. The burning also heats the cup to a high temperature where it becomes incandescent. It is the turbulence and the high cup temperature that give fast burning and the desired large flow range. The flow range for the Selas duradiant burner is 5 to 50 cubic feet/hour of natural gas. Calculations were made for the number of burners required by assuming a temperature range of 1800°R to 3500°R and a velocity range of 25 feet/second to 200 feet/second. The calculations were made at the four extreme conditions and the limiting factors were the maximum and minimum flow of each burner (see Appendix, Section A). From these calculations, twenty burners were determined to be satisfactory. A high velocity was chosen because low velocities can be obtained by shutting off some of the burners. Once the apparatus is operated, the maximum temperature can be determined and the calculations will have to be revised.

The twenty burners, with pieces of firebrick between them, were mounted on the firebrick with Selas 206G sealing cement (Figure VIII). This cement is a heat setting breakable cement good for temperature up to 3000°F. It sets to a hard consistency but can be used for sealing only, not binding. It is recommended that the burners be connected with fitting so a 1/4-inch rubber hose can be used for connecting the manifold to each burner. A rubber hose is advised for easy assembly and as prevention against an explosion in the manifold. Any large pressure rise will just blow the rubber hose off.

Introduction of Diluent

Diluent is necessary to give temperature control of hot products. A non-reactive gas is desired so the fuel-air ratio will not be affected. The fuel-air ratio must always be stoichiometric or extra fuel or air will be present in the mixing zone. The most available non-reactive gas is nitrogen which serves as a good diluent.

The design shows diluent being introduced in one-half inch tubes mounted between each burner at the top of the flow passage. The tubes can be made out of stainless steel or an equivalent high-temperature metal. The tubes were shown at the top of the flow passage. Since the diluent will be cold and the hot gases will have a tendency to rise, the diluent will have a better chance to mix than if it were introduced at the bottom of the passage.

The tubes can be supported by their solid connections or if connected with rubber hoses, they can be supported with the pieces of firebrick that go between the burners and the Selas 206G sealing cement. Some of the pieces of firebrick that go between the burners will have to be removable to permit lighting of the burners with a torch.

Flow Straighteners

The flow out of the burners and from the diluent tubes is not a very smooth, well mixed, or straight flow. Thus, some means were needed to remedy this situation. The ideal device would be a straightening and calming section with a length-diameter ratio of fifty. This would give fully developed flow in the holes and cause mixing, straightening and convert the large-scale turbulence to small-scale turbulence. But, the hot stream being annular would mean that many small holes would have to be radially drilled in an annular section that would be able to withstand the high temperatures of the hot products. If some material of this type could be found, and if it had a fine grain, the smallest practical drill size would be $1/16''$ diameter. This results in a piece over three inches long to give a length-diameter ratio of fifty. This would considerably increase the size of the apparatus.

A material was found that is machinable and will withstand a continuous temperature of 2500°F . It is magnesium

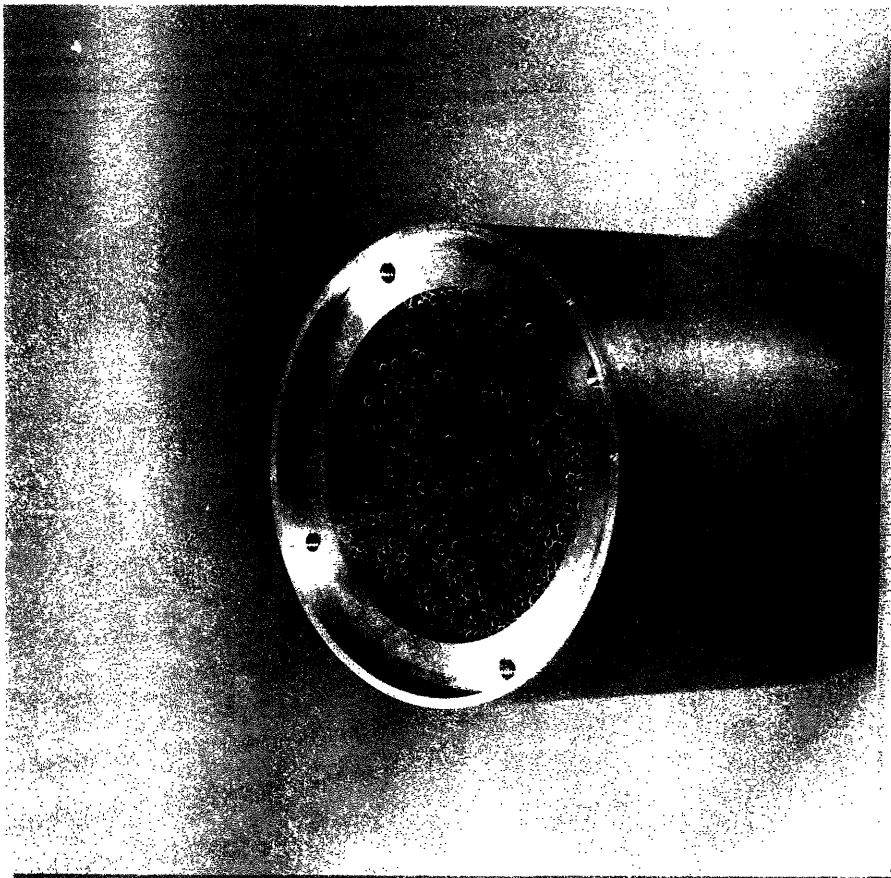
silicate or Alsimag 222 from the American Lava Corporation. The material comes in pieces 4.5" x 4.5" x 7/16" and it is of a porous nature. The company advises that, in machining, a 1/8" wall be maintained. With these results the flow straighteners were designed as pieces 3" x 1-1/2" x 7/16" with 1/8" holes on 1/8" spacing in the 3" x 1-1/2" face. (Figure VIII). The holes are drilled straight through and the pieces are mounted radially in the 3" high flow passage, 2" from the burner outlet with Selas 206G cement. It is realized that this type of straightener will not act as the one previously mentioned but it is a compromise in the design. This grid will tend to mix the products and the diluent because of the pressure gradient across it as well as reduce some turbulence and straighten the flow. The converging section after the straighteners will also help the flow because it will tend to elongate the vortex tubes and decrease the boundary layer thickness.

Cold Combustible Gases Section

The cold combustible gases section is for the introduction of a variable fuel-air mixture into the mixing zone. This section consists of a straightening and calming section and a center tube.

Straightening and Calming Section

This section is shown in Figures IX and XI and is made of aluminum. The purpose of this section is to straighten and



Straightening Section



Converging Section

SIZE-32

FIVE DIVIDED
U.S. STD

FIGURE IX STRAIGHTENING AND CALMING SECTION

calm the mixture that has been piped in. This is done with a straightening tube bundle and converging section. The same theory applies here as it did to the hot products straightening section, but in this case the ideal section could be used.

The straightening tube bundle consists of approximately 880 brass tubes that have $1/8$ " outside diameter and a .014" wall. In order to obtain a length-diameter ratio of 50, a 5" bundle was required. This will result in fully developed flow in the tubes and thus, will decrease the turbulence.

The next part of the section is a converging section from 4.04" to 1.5". It consists of two cubic curves and will serve to improve the flow pattern by decreasing the boundary layer thickness and elongating the vortex tubes.

The whole section is mounted to the bottom enclosure on the bolts that were previously discussed, with nuts and Selsas 206-G cement on the face to act as a sealer. A four-inch pipe with a flange can be connected to the inlet with bolts and can be sealed with a standard Parker 2-156 O-ring.

Quite a dilemma occurred over the placement of the straightening and calming section. One argument was to place it as close to the mixing zone as possible so as to keep the boundary layer thickness to a minimum but at the sacrifice of the insulating center enclosure. The other argument was

to place the section at the bottom of the bottom enclosure to take full advantage of the insulation at the sacrifice of the boundary layer thickness. An evaluation of the effect of the length on the boundary layer thickness (Appendix 1, Section A) and the fact that the center enclosure would be a much more complicated casting, determined the choice of putting the section at the bottom of the bottom enclosure as it is shown.

Center Tube

The center tube is one of the most important portions of this apparatus because it constitutes the point where the hot and cold stream will mix. (Figure X) . The tube is shown in the design as a hollow cylinder 9.6" long with a 2" o.d. and a 1-1/2" i.d. The tip has the contour of the beginning of the inner cubic curve which makes a thin section at the tip.

The actual tube is this size and made of alundum. Alundum is aluminum oxide that is very hard and will withstand temperatures as high as 2640°F. Grinding is required to machine it.

The tube was machined by mounting it in a lathe and machining the contour with a diamond. The diamond was a grinding wheel dresser. The contour was made following a template.

The tube mounts in the middle of the center enclosure and rests on the aluminum straightening and calming section.

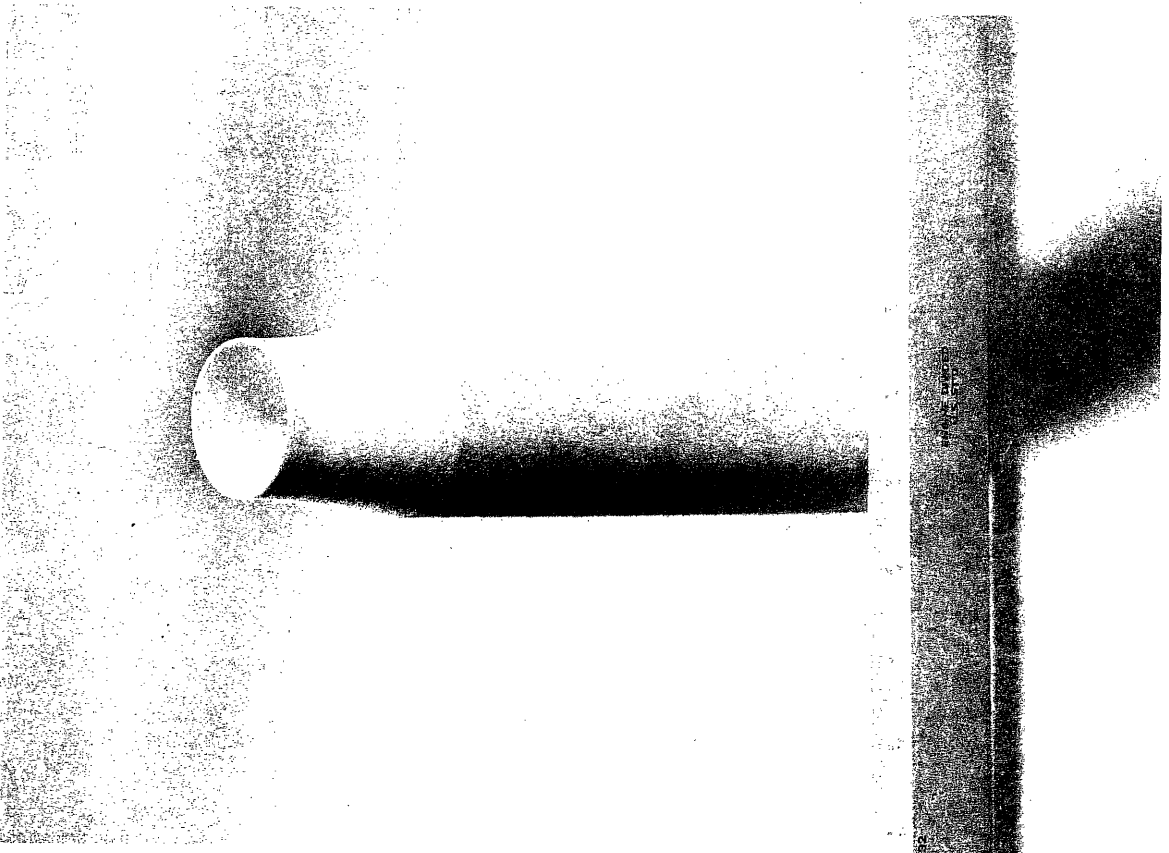


FIGURE X CENTER TUBE

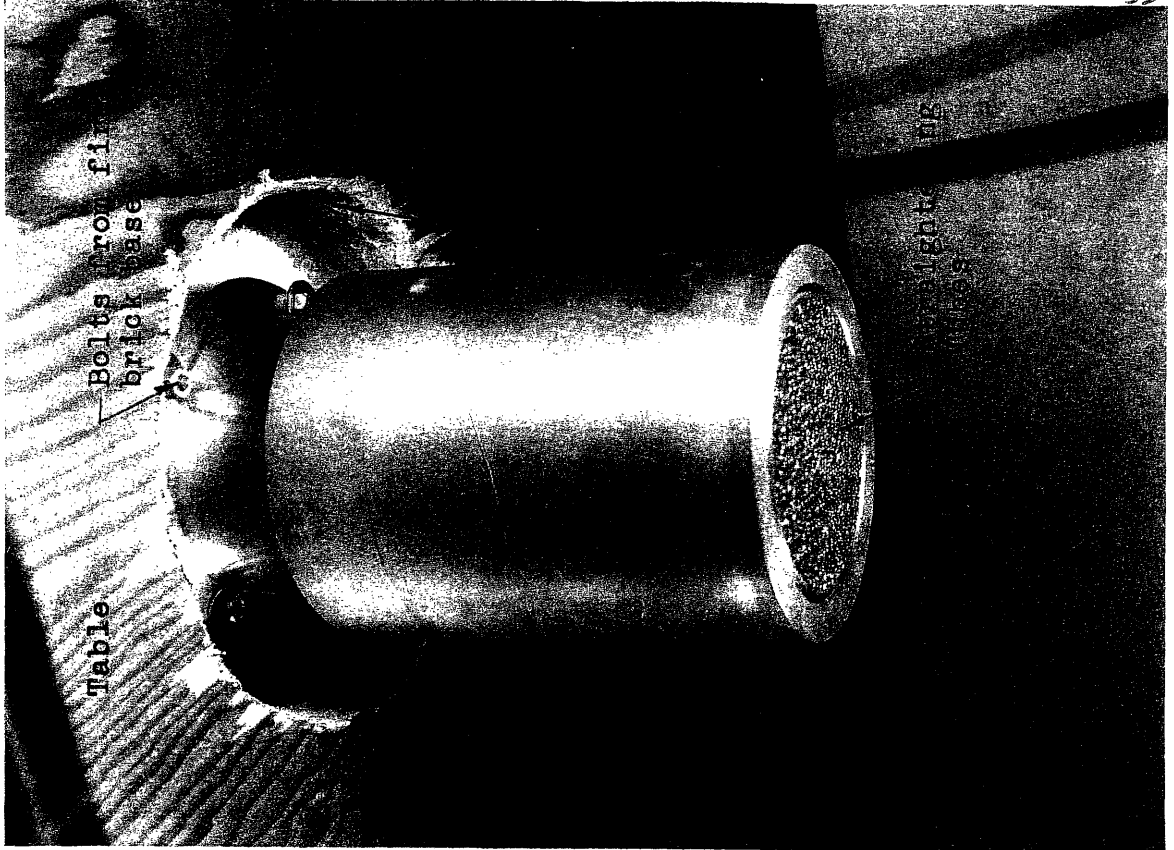


FIGURE XI BOTTOM OF FINAL APPARATUS

Selas 206-G was used on the outside and bottom of the tube as well as used to blend the curve from the tube to the center enclosure.

The tube may not be satisfactory if it burns at the thin section. In this case it may be advisable to make a removable tip so another could be inserted. Also if the flame that is initiated above the center tube flashes back it may burn the straightening tubes. If this happens then a quenching screen will have to be placed in the center tube, which could be done by inserting it under the removable tip. These two designs would have been incorporated in the apparatus but a two-piece tube is much more complicated than a one-piece tube especially if it is not necessary. Also the idea of using or not using a quenching screen is quite a dilemma because, as stated previously, a flash-back may burn up the straightening tube, but a quenching screen will put turbulence back into the flow that was so painstakingly taken out. Thus, these two items were left until testing can be performed.

External Sections

The only sections external to the actual apparatus are the aforementioned pyrex tube and sheet metal chimney. (Figure XII). The pyrex tube can be set on the metal housing of the top enclosure and sealed with Selas 206-G cement. If the pyrex tube is not adequate for testing purposes, a vycor tube can withstand higher temperatures than pyrex but a piece

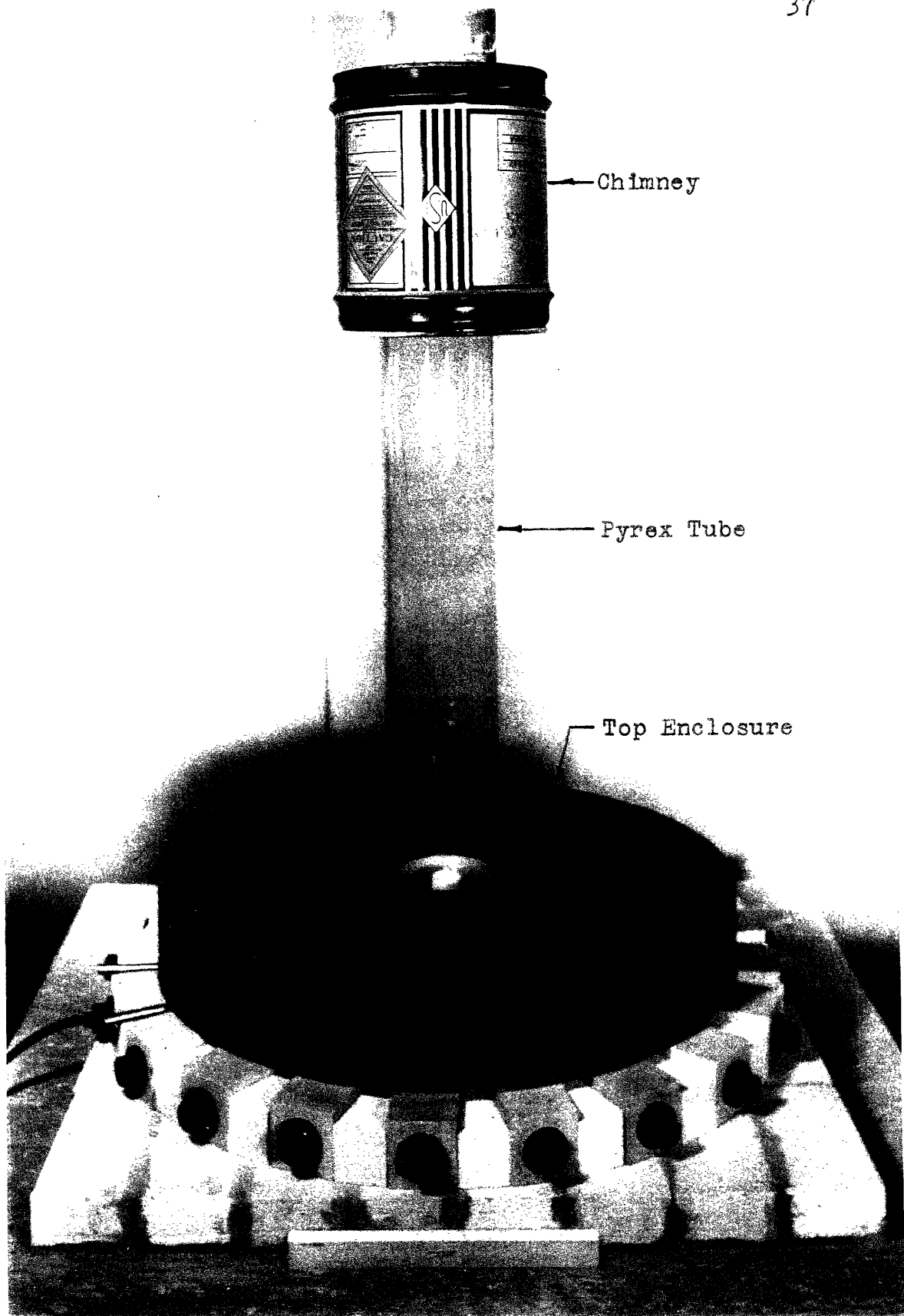


FIGURE XII FINAL APPARATUS-CLOSED POSITION

with 6" o.d. and 21" long is priced at \$233.80. It will be necessary to rearrange the chimney to have it situated over the pyrex tube but otherwise it should be thoroughly adequate for an exhaust system.

Conclusions

The final apparatus incorporated all the ideas from the preliminary testing apparatus which includes a hot combustion products section, a cold combustible gases section and an external section. The hot products section has enough burners to permit a large flow range and diluent to permit a large temperature control. The section has flow straighteners that are not fully adequate but are a compromise between a theoretical straightening section and the material-size-machining problem. The section has a converging flow path to perfect the flow pattern and a zero slope curve at the mixing point.

The cold gases section has a straightening and calming section for control of an unfavorable flow pattern. It has an insulated center tube (insulated by the center enclosure, an air space and the center tube) plus a thin section at the mixing point.

The external section has a pyrex tube to permit visual observation of the initiated flame and a chimney to exhaust the burned and unburned gases.

These three sections, the hot combustion products section, the cold combustible gases section and the external section constitute the final apparatus for studying combustion in a laminar mixing zone.

APPENDIX

APPENDIX, SECTION A
CALCULATIONS

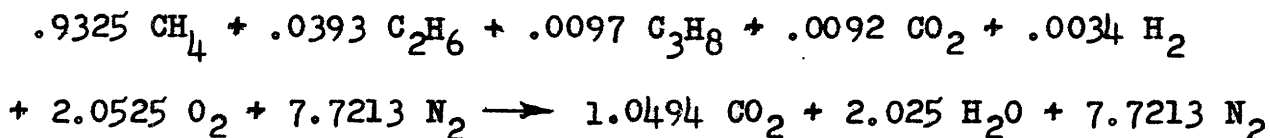
Calculation of the Stoichiometric Fuel-air Ratio for Cambridge

Natural Gas

Percentages reported as follows from the Gas Company:

CH ₄	93.25%
C ₂ H ₆	3.93%
C ₃ H ₈	.97%
CO ₂	.92%
H ₂	.34%
Others	<u>.59%</u>
	100.00%

Balancing the chemical equation, assuming complete combustion



Air required

$$2.0525 \text{ moles O}_2 \times 32 \text{ lb/mole} = 65.68 \text{ lb}$$

$$7.7213 \text{ moles N}_2 \times 28.16 \text{ lb/mole} = 217.43 \text{ lb}$$

$$\text{lbs air required} = 283.11$$

Fuel required

$$\text{CH}_4 \quad .9325 \text{ moles} \times 16 \text{ lb/mole} = 14.92 \text{ lb}$$

$$\text{C}_2\text{H}_6 \quad .0393 \text{ moles} \times 30 \text{ lb/mole} = 1.18 \text{ lb}$$

$$\text{C}_3\text{H}_8 \quad .0097 \text{ moles} \times 44 \text{ lb/mole} = .426 \text{ lb}$$

$$\text{CO}_2 \quad .0092 \text{ moles} \times 44 \text{ lb/mole} = .405 \text{ lb}$$

$$\text{H}_2 \quad .0034 \text{ moles} \times 2 \text{ lb/mole} = .0068 \text{ lb}$$

$$\underline{16.9378 \text{ lb}}$$

Fuel required = 16.9378 lbs

$$\left(\frac{F}{A}\right)_{\text{stoichiometric}} = \frac{16.9378}{283.11} = .0598$$

Calculation of Flow Area of Hot Stream

hole in top enclosure = 5.625 inches

diameter of center tube = 1.5 inches

$$A = \frac{\pi D_h^2}{4} - \frac{\pi D_t^2}{4}$$

$$A = \frac{\pi(5.625)^2}{4} - \frac{\pi(1.5)^2}{4} = 24.85 - 1.77$$

$$A = 23.08 \text{ sq. in.} \times \frac{\text{sq. ft.}}{144 \text{ sq. in.}} = .1605 \text{ sq. ft.}$$

$$A = .1605 \text{ sq. ft.}$$

Calculation for Number of Burners

velocity range	25-200 ft/sec
temperature range	1800°R - 3500°R
burner flow range	5 - 50 cu.ft. fuel/hr. (Selas Bulletin C-1037)

Number of burners must be adequate so for over the ranges listed above the burners are not operating above or below their capacity.

For flow at $V = 200 \text{ ft/sec}$

$$T = 3500^\circ\text{R}$$

$$A = .1605 \text{ sq. ft.}$$

$$\rho = .01135 \text{ lb/cu.ft.}$$

$$\rho AV = \frac{.01135 \text{ lb}}{\text{cu.ft.}} \times .1605 \text{ sq.ft.} \times \frac{200 \text{ ft.}}{\text{sec.}} = .364 \frac{\text{lb. mix.}}{\text{sec.}}$$

$$\frac{.364 \text{ lb.mix.}}{\text{sec.}} \times \frac{.06 \text{ lb.fuel}}{1.06 \text{ lb.mix.}} \times \frac{3600 \text{ sec.}}{\text{hr.}} = 74.2 \frac{\text{lb.fuel}}{\text{hr.}}$$

$$\frac{74.2 \text{ lb.fuel}}{\text{hr.}} \times \frac{\text{cu.ft.}}{.075 \text{ lb.}} = 990 \frac{\text{cu.ft. fuel}}{\text{hr.}}$$

Number of burners required so not to exceed $\frac{50 \text{ cu.ft. fuel}}{\text{hr.}} = n$

$$n = \frac{990}{50} = 19.8$$

Thus, need more than 19.8 burners for this condition

For flow at $V = 25 \text{ ft/sec}$

$$T = 3500^\circ\text{R}$$

$$A = .1605 \text{ sq.ft.}$$

$$\rho = .01135 \text{ lb/cu.ft.}$$

$$\rho AV = (.01135)(.1605)(25) = .0456 \frac{\text{lb.mix.}}{\text{sec.}}$$

$$\frac{(.045)(.06)(3600)}{1.06} = 9.16 \frac{\text{lb.fuel}}{\text{hr.}}$$

$$\frac{9.16}{.075} = 122 \frac{\text{cu.ft. fuel}}{\text{hr.}}$$

Number of burners required so not to be less than

$$\frac{5 \text{ cu.ft.fuel}}{\text{hr.}} = n$$

$$n = \frac{122}{5} = 24.4$$

Thus, need less than 24.4 burners for this condition

For flow at: $V = 200 \text{ ft/sec.}$

$$T = 1800^\circ\text{R}$$

$$A = .1605 \text{ sq.ft.}$$

$$\rho = .0221 \text{ lb/cu.ft.}$$

$$\rho AV = (.0221)(.1605)(200) = .711 \frac{\text{lb.mix.}}{\text{sec.}}$$

But dilutent was required to get down to 1800°R which is part of the $.711 \text{ lb.mix./sec.}$ and

$$(WC_p \Delta T)_{\text{nitrogen}} = (WC_p \Delta T)_{\text{products}}$$

$$(W)(.24)(1800-530) = (W)(.24)(3500-1800)$$

$$\frac{W_{\text{nitrogen}}}{W_{\text{products}}} = \frac{1700}{1270} = 1.338$$

$$\text{but } W_{\text{nitrogen}} + W_{\text{products}} = .711 \text{ lb.mix./sec.}$$

$$2.338 W_{\text{products}} = .711$$

$$W_{\text{products}} = .304 \text{ lb.products/sec.}$$

$$\frac{(.304)(.06)(3600)}{1.06} = 62 \frac{\text{lb. fuel}}{\text{hr.}}$$

$$\frac{62}{.075} = 827 \frac{\text{cu. ft. fuel}}{\text{hr.}}$$

Number of burners required so not to exceed 50 cu.ft.fuel/hr = n

$$n = \frac{827}{50} = 16.5$$

Thus, need more than 16.5 burners for this condition.

For flow at $V = 25 \text{ ft./sec.}$

$$T = 1800^{\circ}\text{R}$$

$$A = .1605 \text{ sq.ft.}$$

$$\rho = .0221 \text{ lb./cu.ft.}$$

$$\rho AV = (.0221)(.1605)(25) = .0887 \text{ lb.mix./sec.}$$

$$W_{\text{nitrogen}} + W_{\text{products}} = .0887 \text{ lb/mix.sec.}$$

$$2.338 W_{\text{products}} = .0887$$

$$W_{\text{products}} = .038 \text{ lb.products/sec.}$$

$$\frac{(.038)(.06)(3600)}{1.06} = 7.75 \frac{\text{lb. fuel}}{\text{hr.}}$$

$$\frac{7.75}{.075} = 103.2 \frac{\text{cu. ft. fuel}}{\text{hr.}}$$

Number of burners required so not to be less than $\frac{5 \text{ cu. ft. fuel}}{\text{hr.}} = n$

$$n = \frac{103.2}{5} = 20.6$$

Thus, need less than 20.6 burners for this condition.

Looking at all these conditions it is obvious that the number of burners required is 20.

Calculation for Boundary Layer Thickness at Two Positions of the Straightening and Calming Section

The worst conditions were taken for these calculations which are low velocity and high temperature.

Assuming the Section is at the bottom of the bottom enclosure the following conditions prevail:

$$X = 9.6'' \text{ (assuming the main boundary layer growth is after the straightening and calming section)}$$

$$V = 25 \text{ ft./sec.}$$

$$T = 70^\circ\text{F (no heating from hot stream)}$$

$$\rho = .075 \text{ lb/cu.ft.}$$

$$\mu = .0177 \times 2.42 \text{ lb/hr.ft.}$$

Using the exact solution for the boundary layer thickness

$$\delta = 5\sqrt{\frac{\mu X}{V\rho}}$$

$$\delta = 5\sqrt{\frac{(.0177)(2.42)(9.6)(12) \text{ lb.in.sec.(cu.ft.)hr.in.}}{(25)(.075)(3600) \text{ hr.ft.ft.lb.sec.ft.}}}$$

$$\delta = 5\sqrt{.00073 \text{ sq.in.}} = (5)(.02705) \text{ in.}$$

$$\delta = .135 \text{ inches}$$

Assuming the section to be as close to the mixing zone as possible the following conditions prevail:

$$X = 3''$$

$$V = 25 \text{ ft./sec.}$$

$$T = 800^\circ\text{F (heated from hot stream)}$$

$$\rho = .0315 \text{ lb/cu.ft.}$$

$$\mu = .0327 \times 2.42 \text{ lb/hr.ft.}$$

$$\delta = 5 \sqrt{\frac{\mu X}{V \rho}}$$

$$\delta = 5 \sqrt{\frac{(.0327)(2.42)(3)(12) \text{ sq.in.}}{(25)(.0315)(3600)}}$$

$$\delta = 5 \sqrt{.0010 \text{ sq in.}} = (5)(.0317) \text{ inches}$$

$$\delta = .1585 \text{ inches}$$

Thus, it is seen that the boundary layer is thinner when the section is mounted at the bottom of the bottom enclosure, even though the distance is larger, the insulation and simplicity of design are greater.

APPENDIX, SECTION B

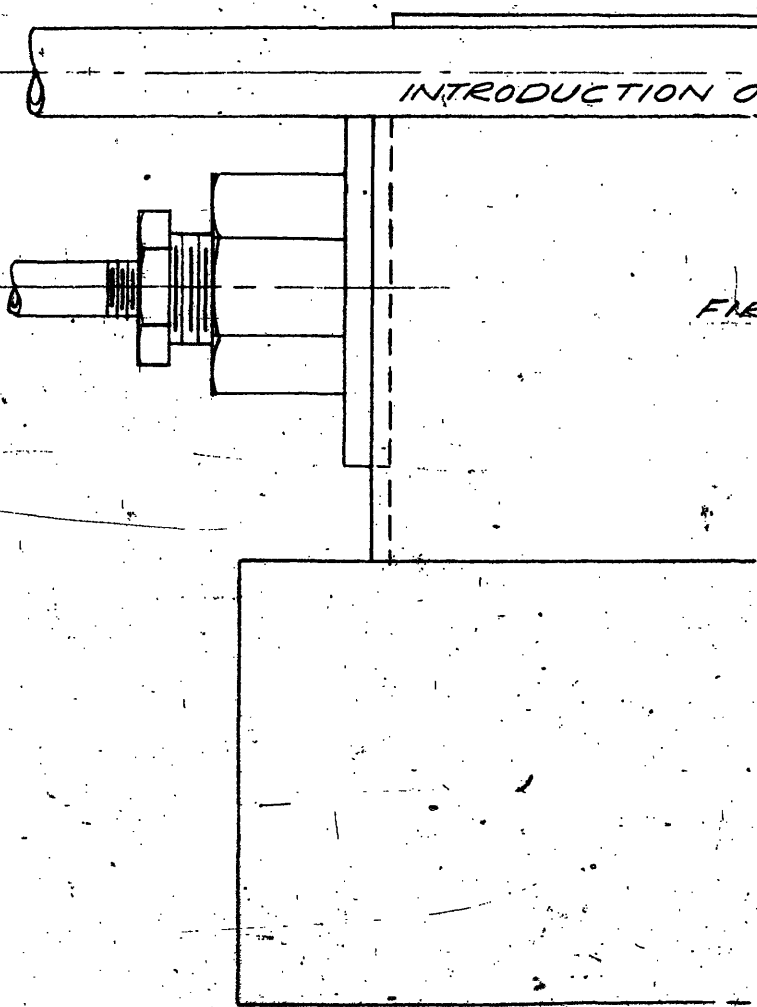
DESIGN

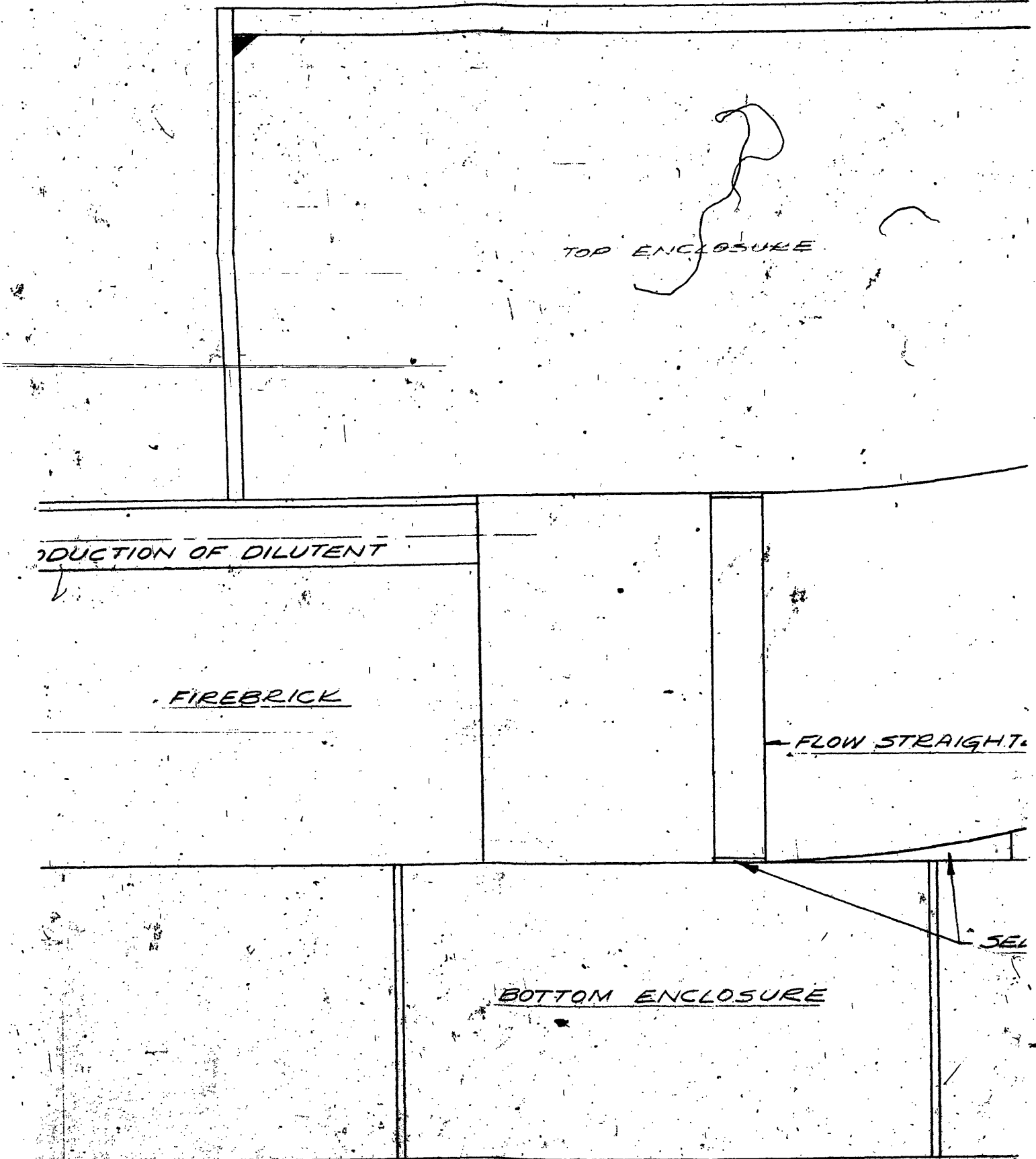
TO MANIFOLD

INTRODUCTION O.

RUBBER HOSE CONNECTION.

F1E





TOP ENCLOSURE

INDUCTION OF DILUTENT

FIREBRICK

FLOW STRAIGHT

BOTTOM ENCLOSURE

SEL

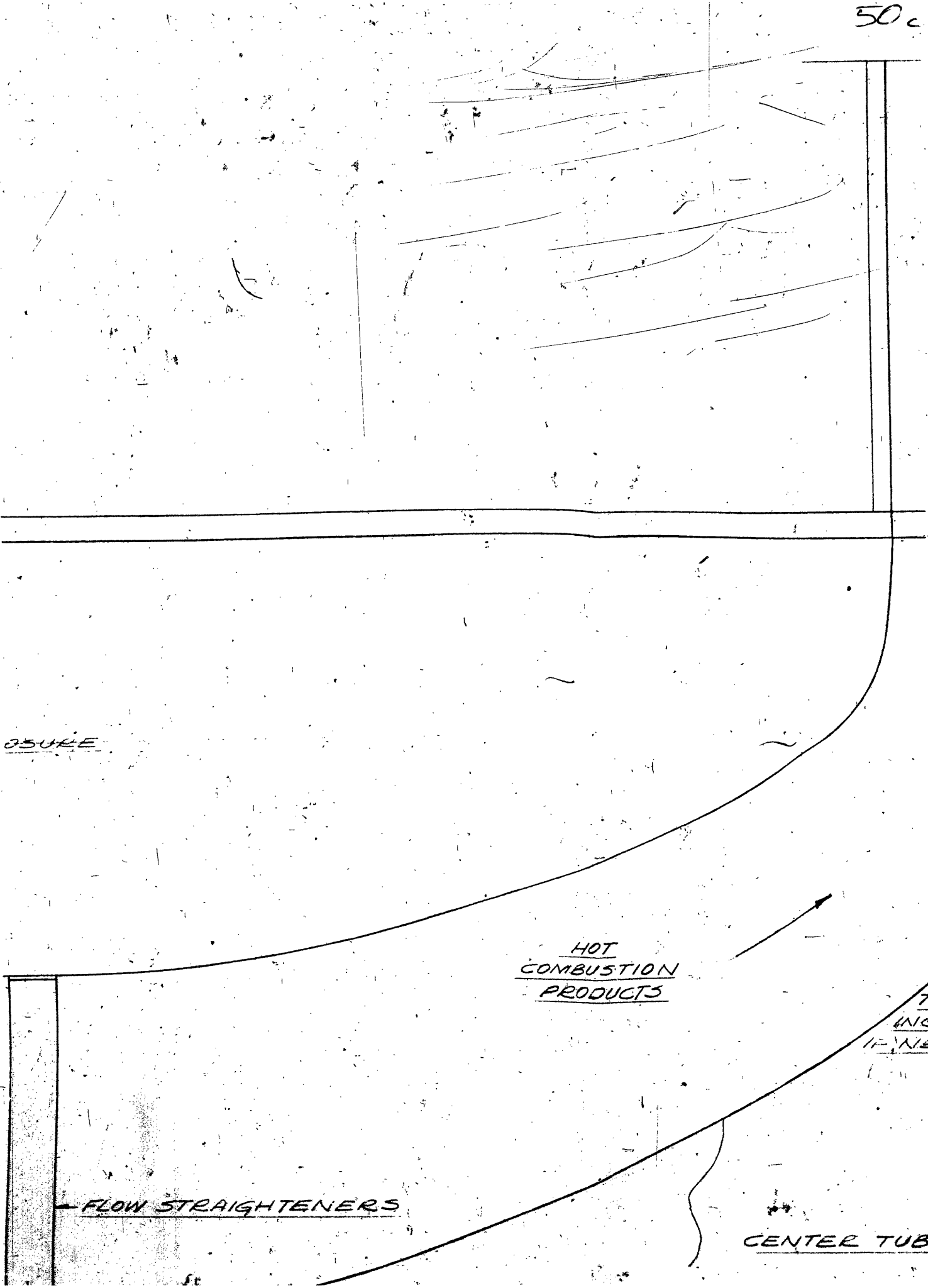
ASURE

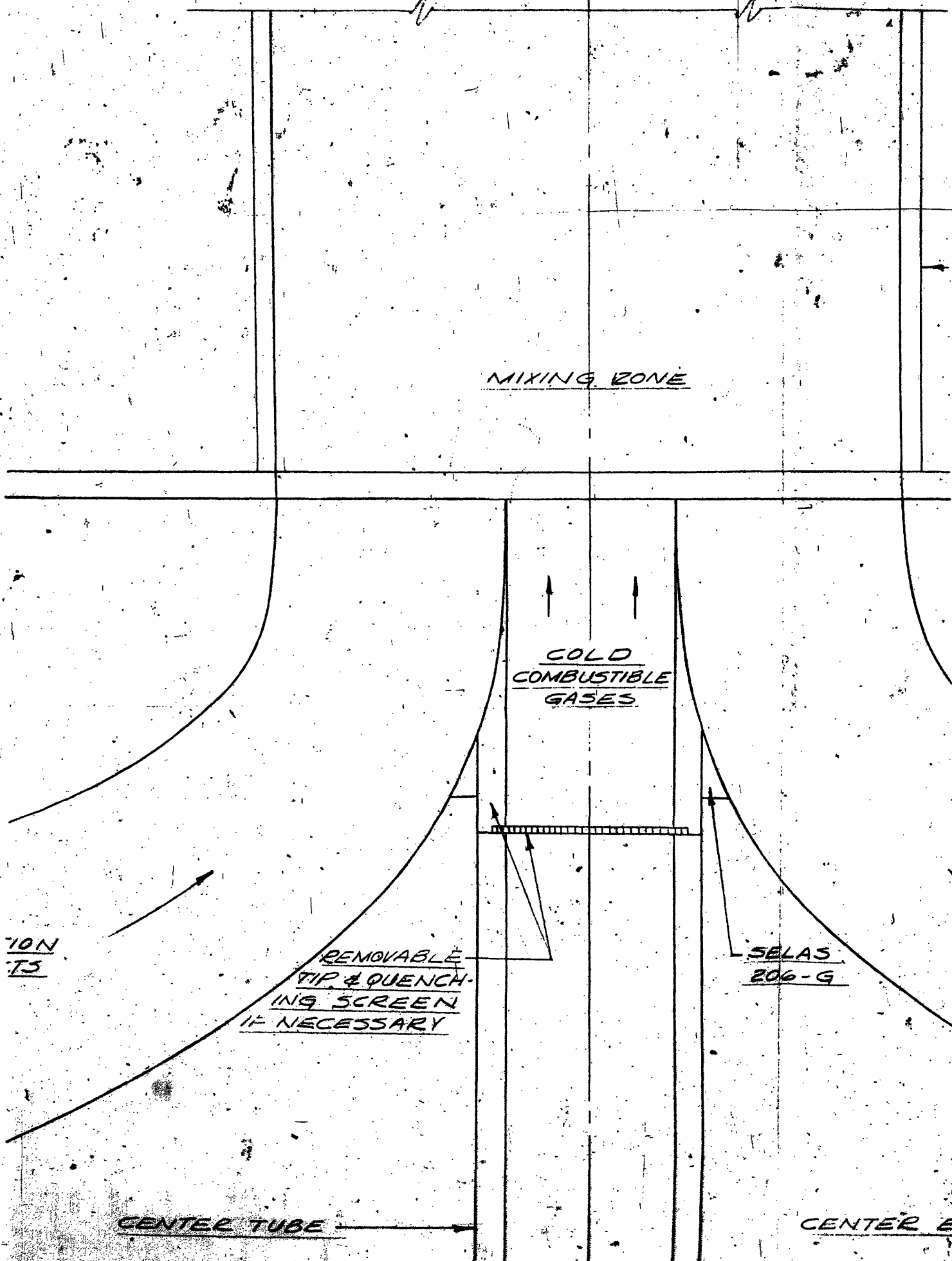
HOT
COMBUSTION
PRODUCTS

7
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FLOW STRAIGHTENERS

CENTER TUBE





MIXING ZONE

COLD
COMBUSTIBLE
GASES

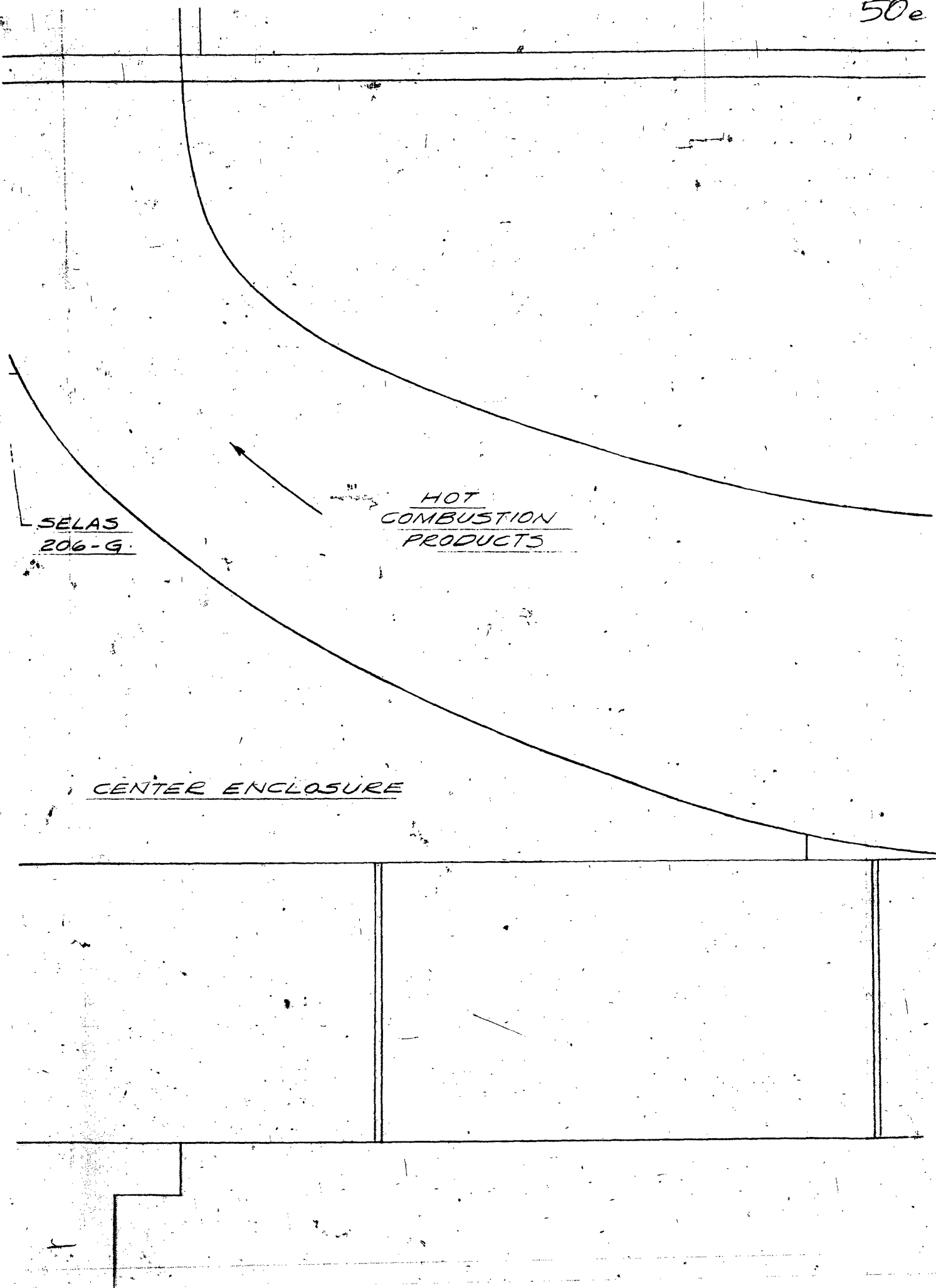
REMOVABLE
TIP & QUENCH-
ING SCREEN
IF NECESSARY

70N
TS

SELAS
206-G

CENTER TUBE

CENTER E



SELAS
206-G

HOT
COMBUSTION
PRODUCTS

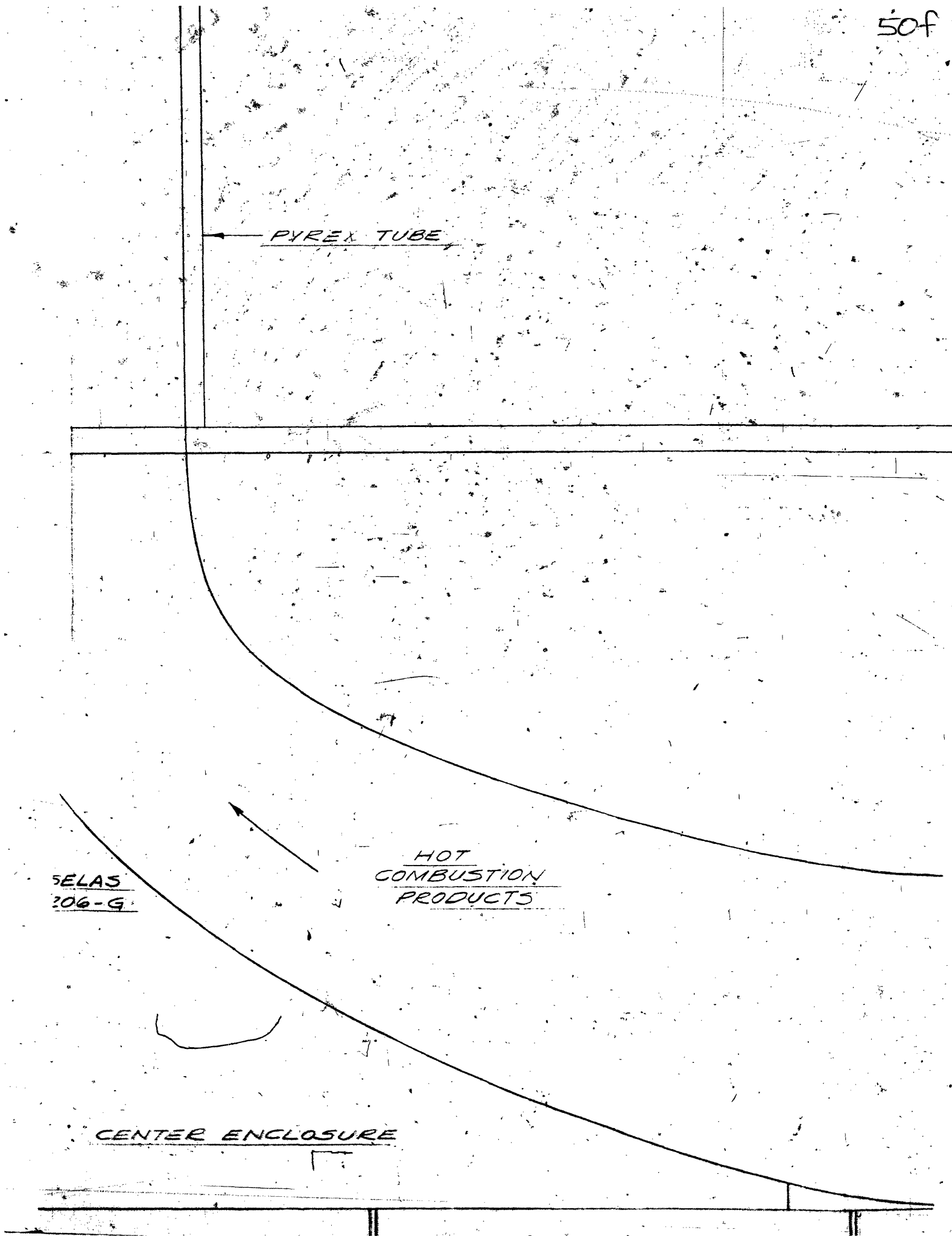
CENTER ENCLOSURE

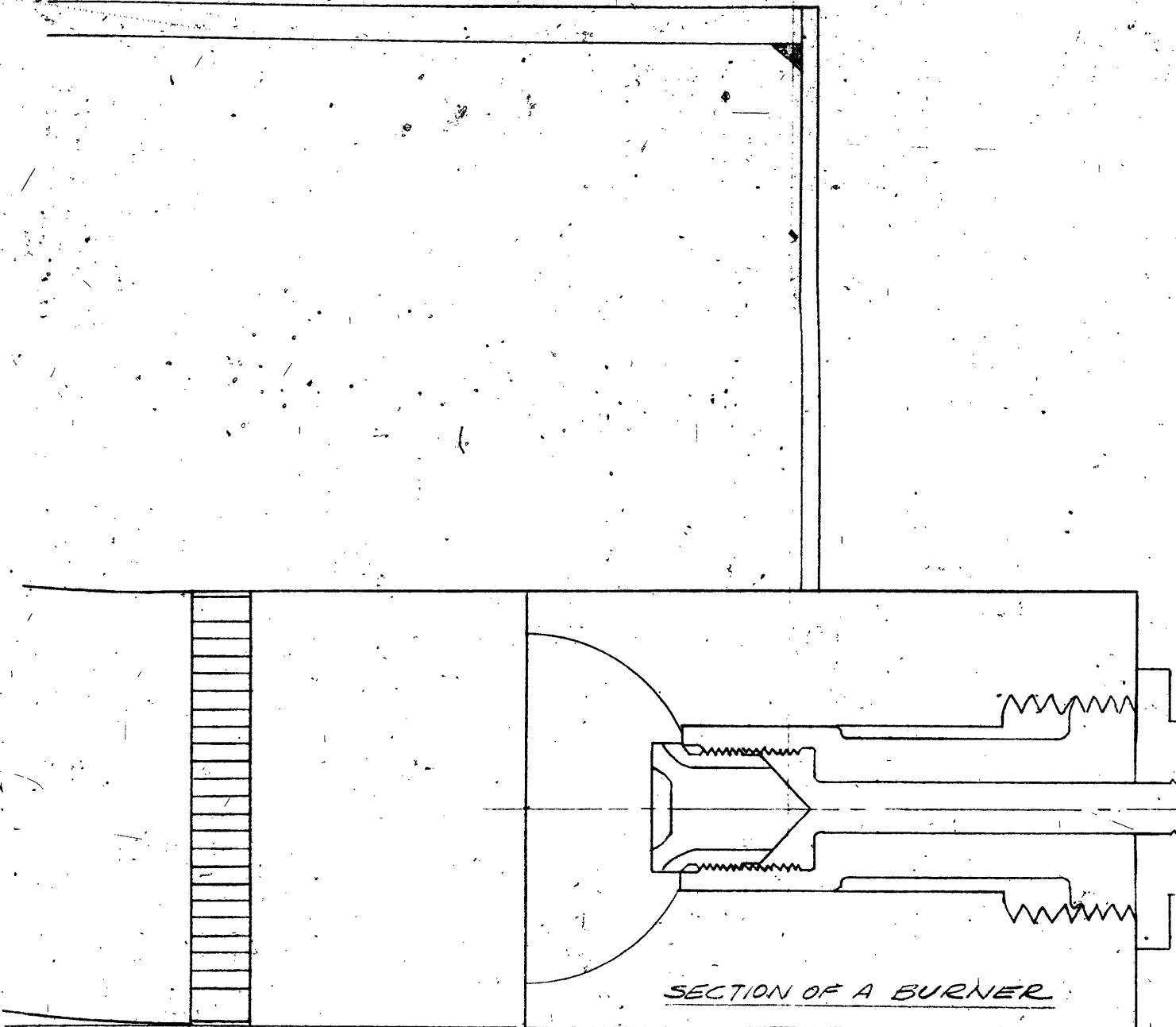
PYREX TUBE

HOT
COMBUSTION
PRODUCTS

SELAS
206-G

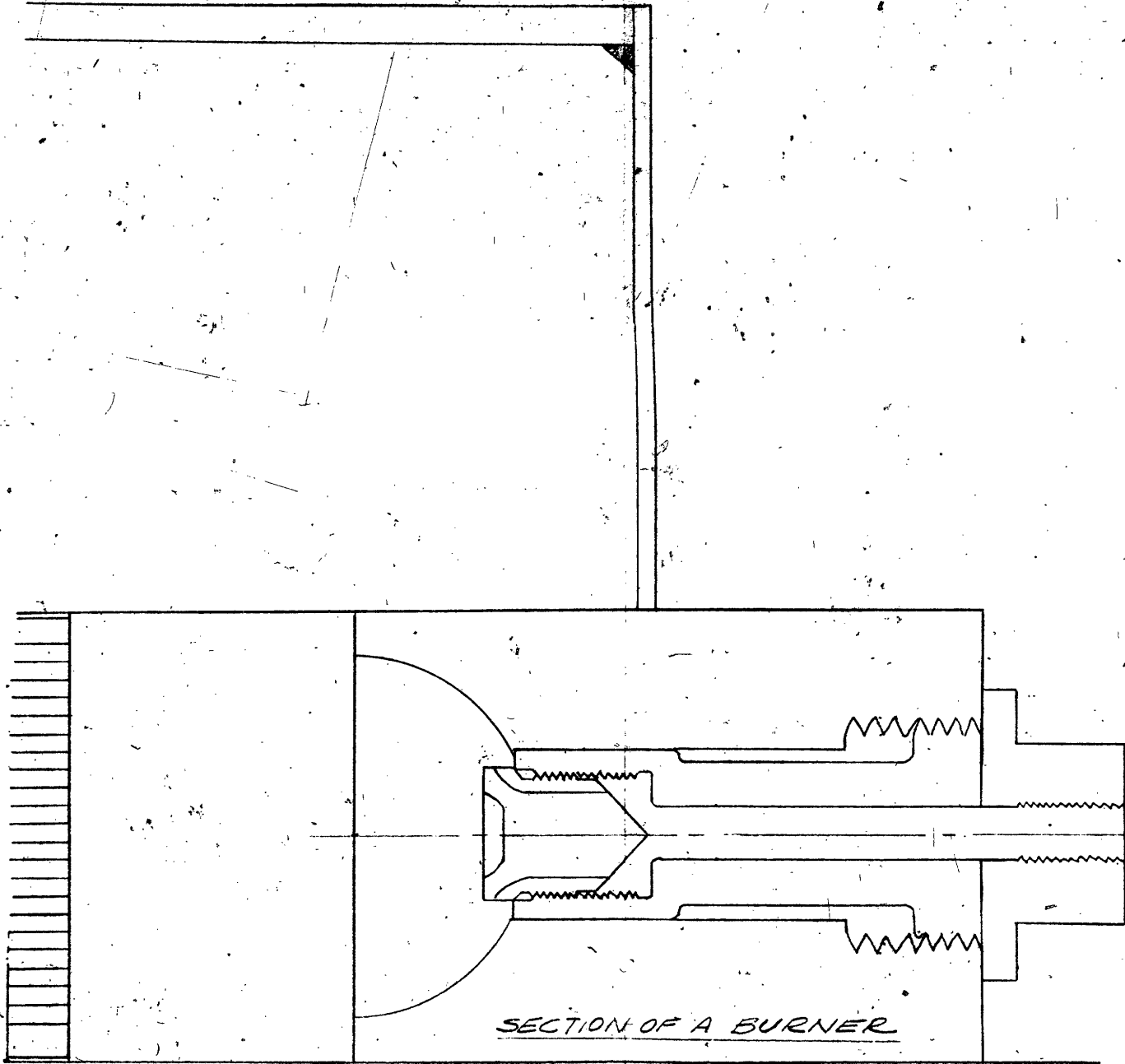
CENTER ENCLOSURE





SECTION OF A BURNER

BOTTOM ENCLOSURE



TOM ENCLOSURE

COLD
COMBUSTIBLE
GASES.

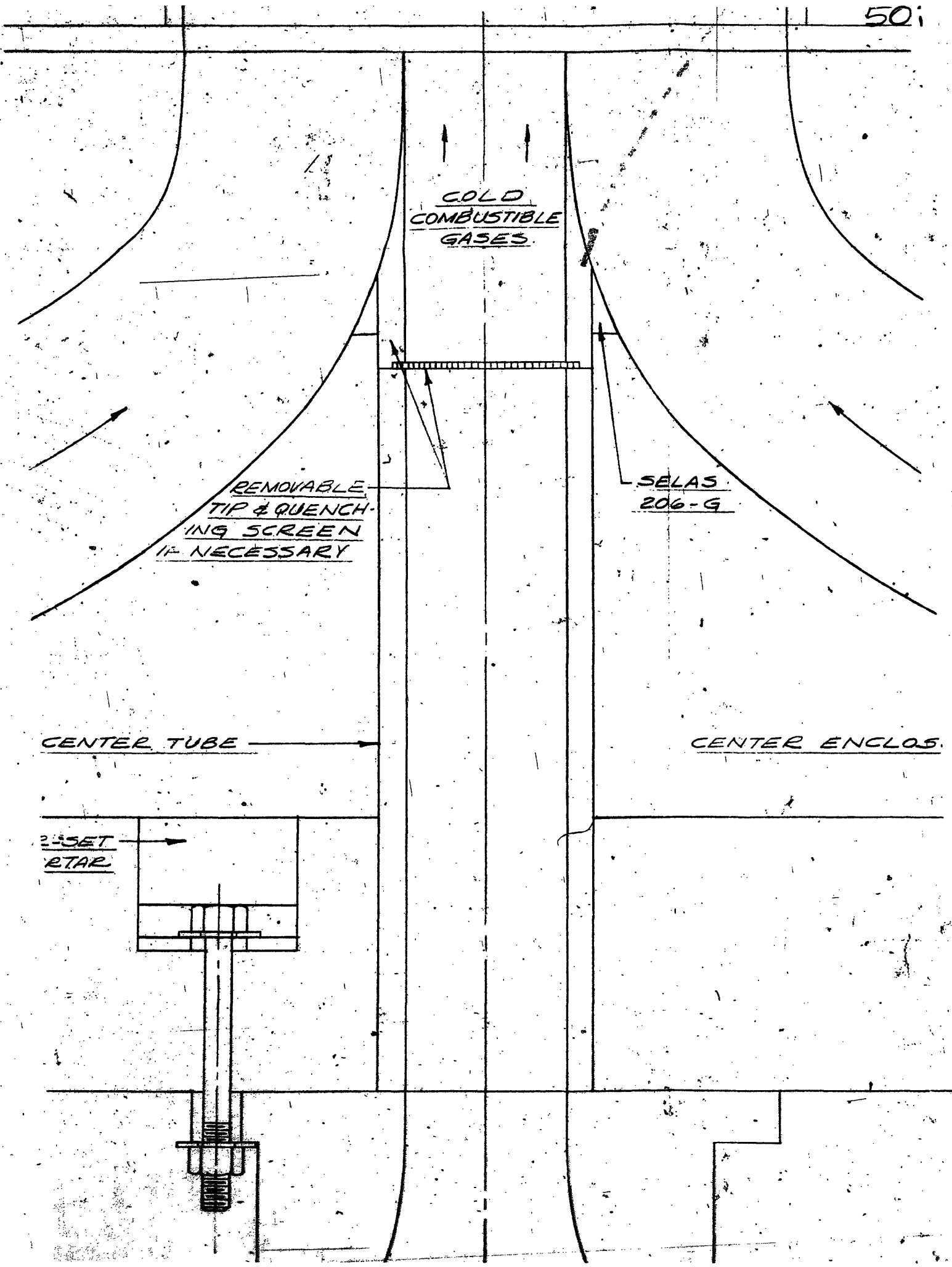
REMOVABLE
TIP & QUENCH-
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IF NECESSARY

SELAS
206-G

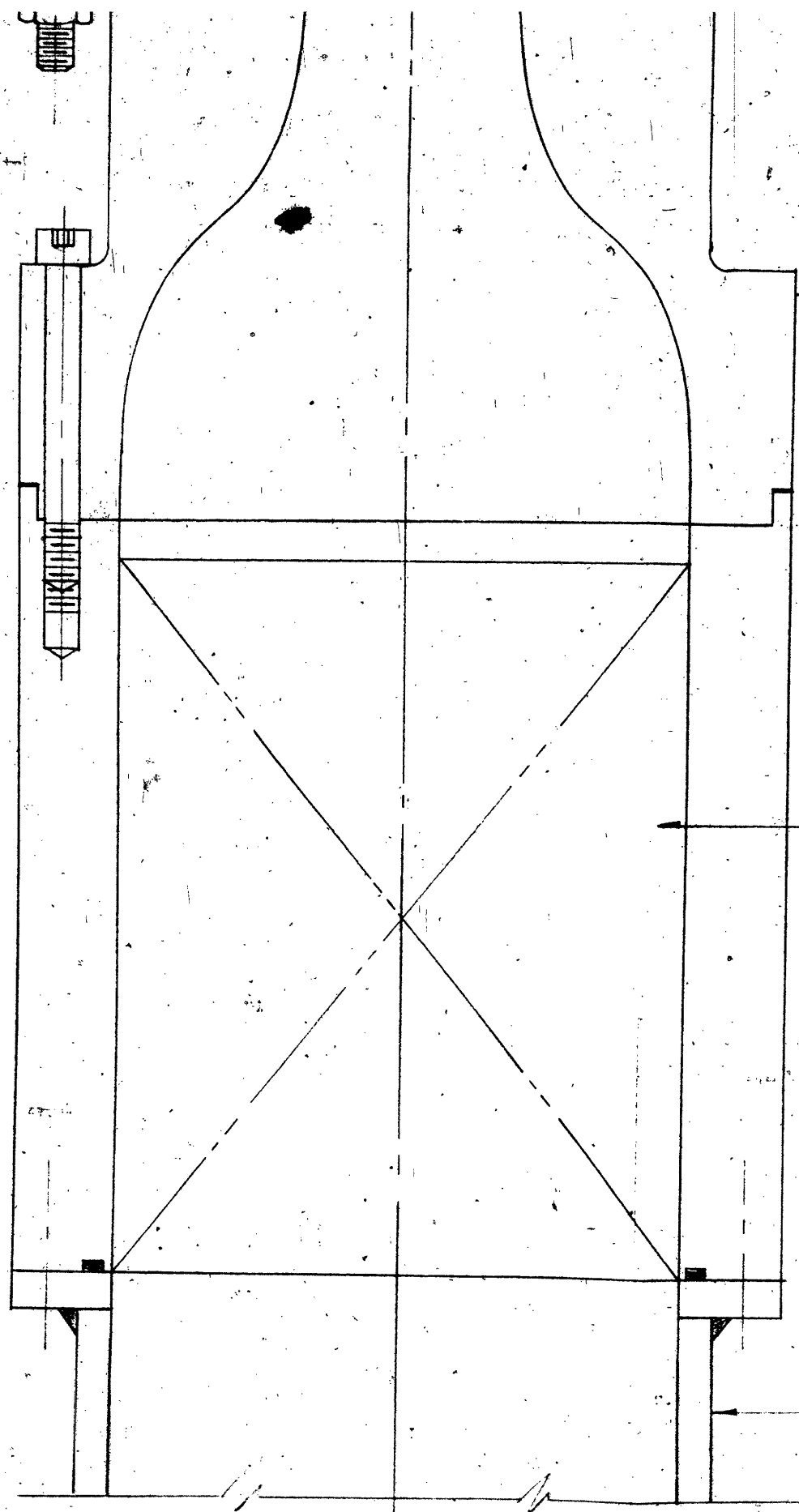
CENTER TUBE

CENTER ENCLOS.

RESET
START



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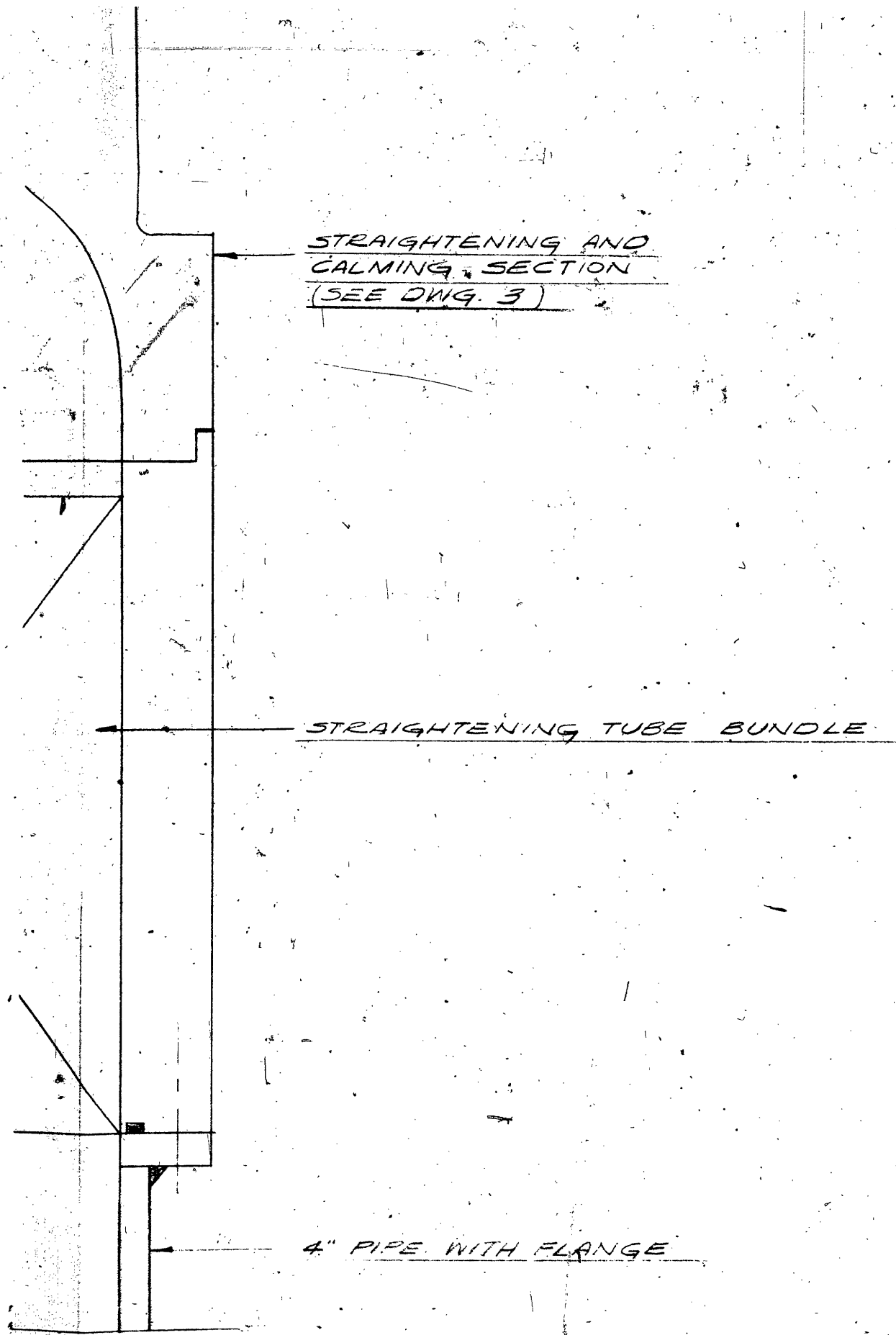


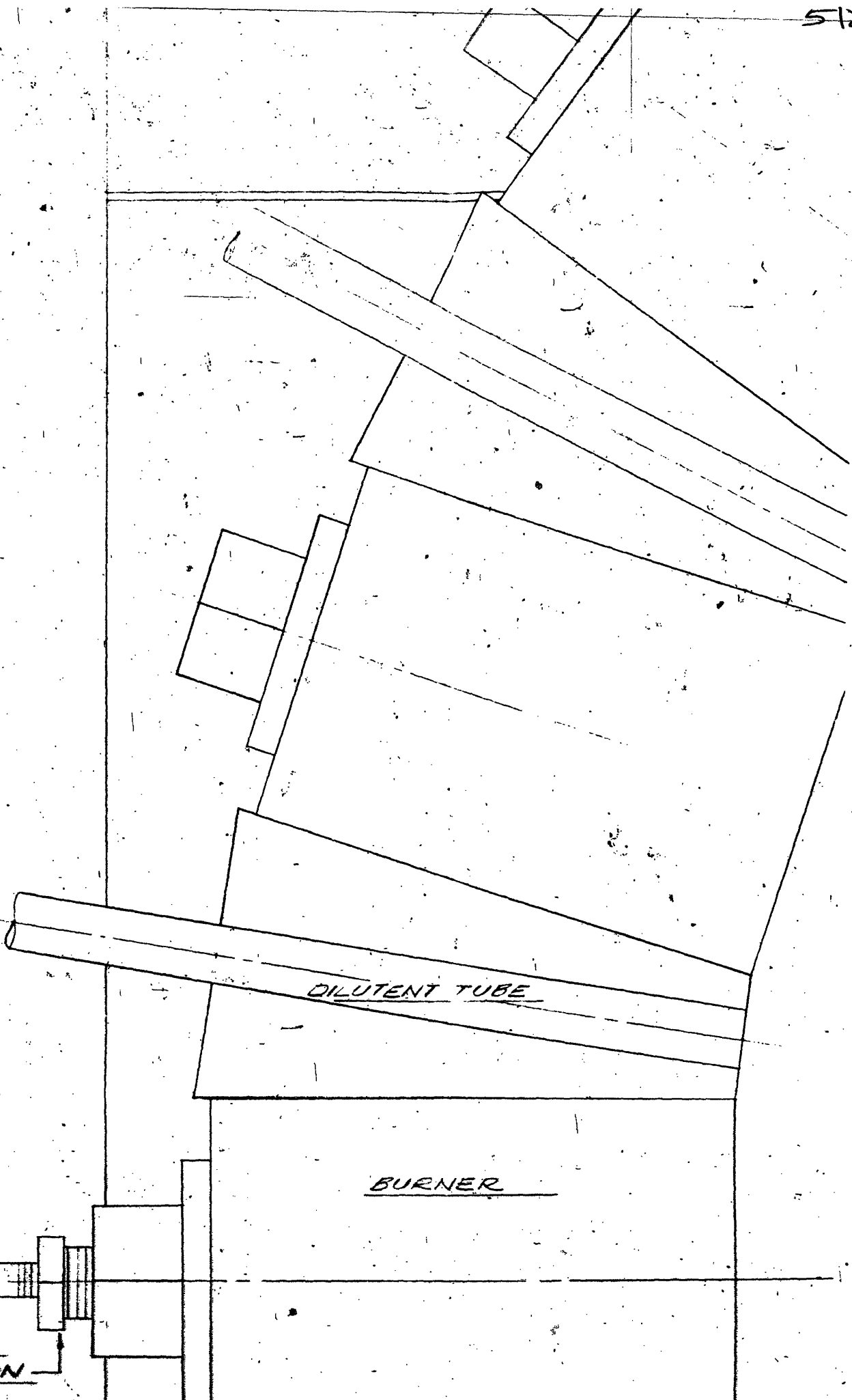
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CALM
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STRAI

4" PIP.

SECTION AA (SEE DWG. 2)

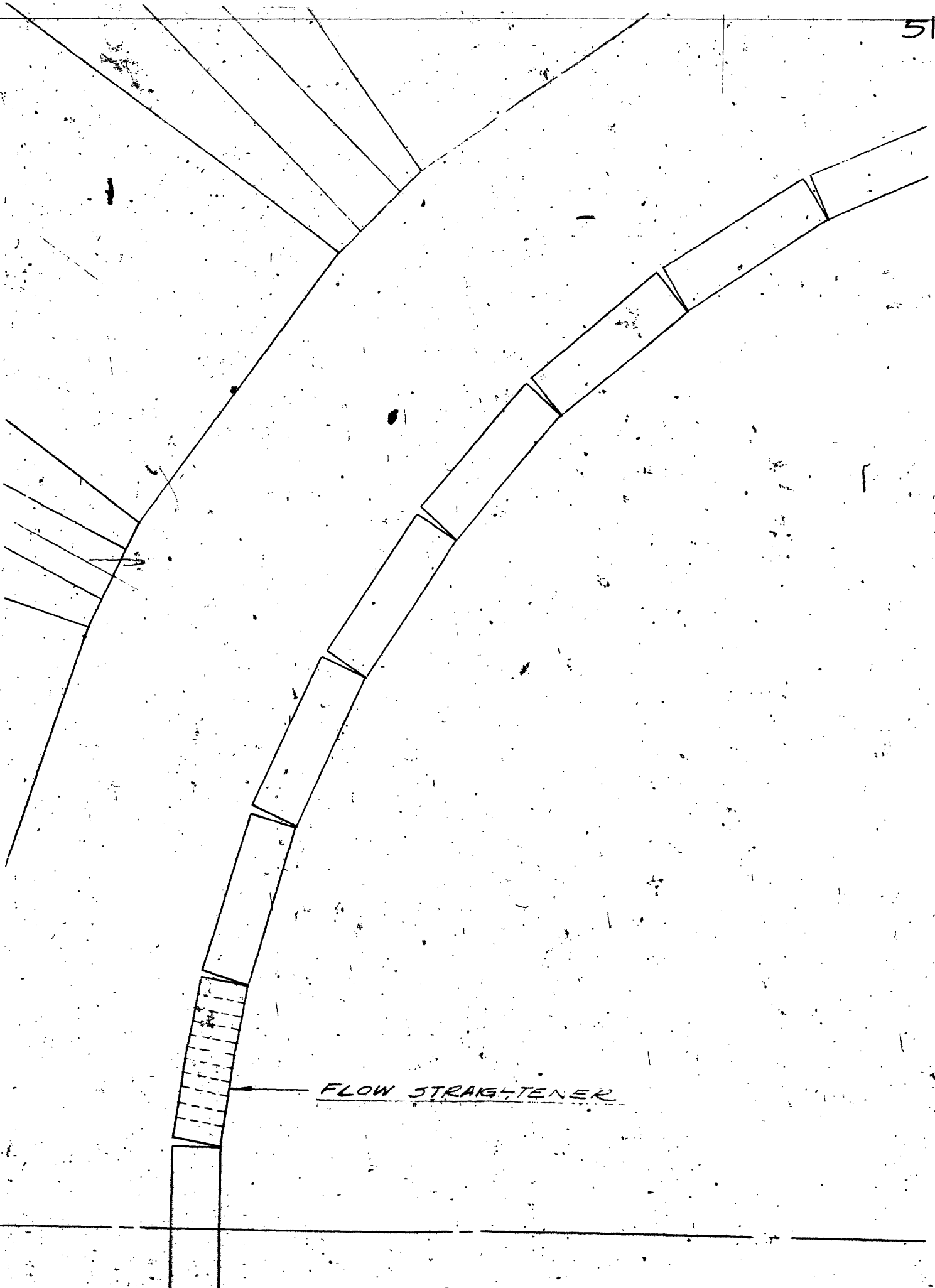




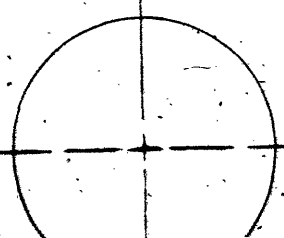
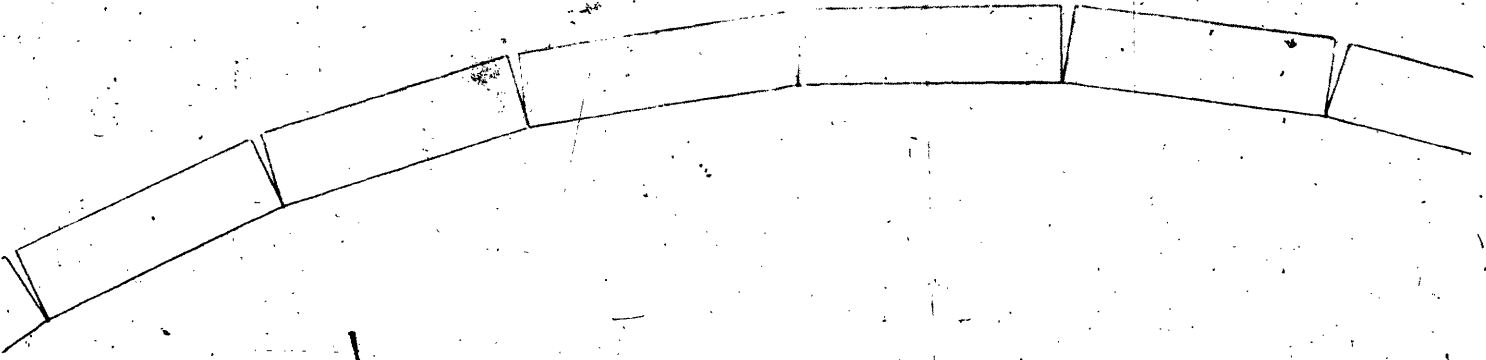
DILUTENT TUBE

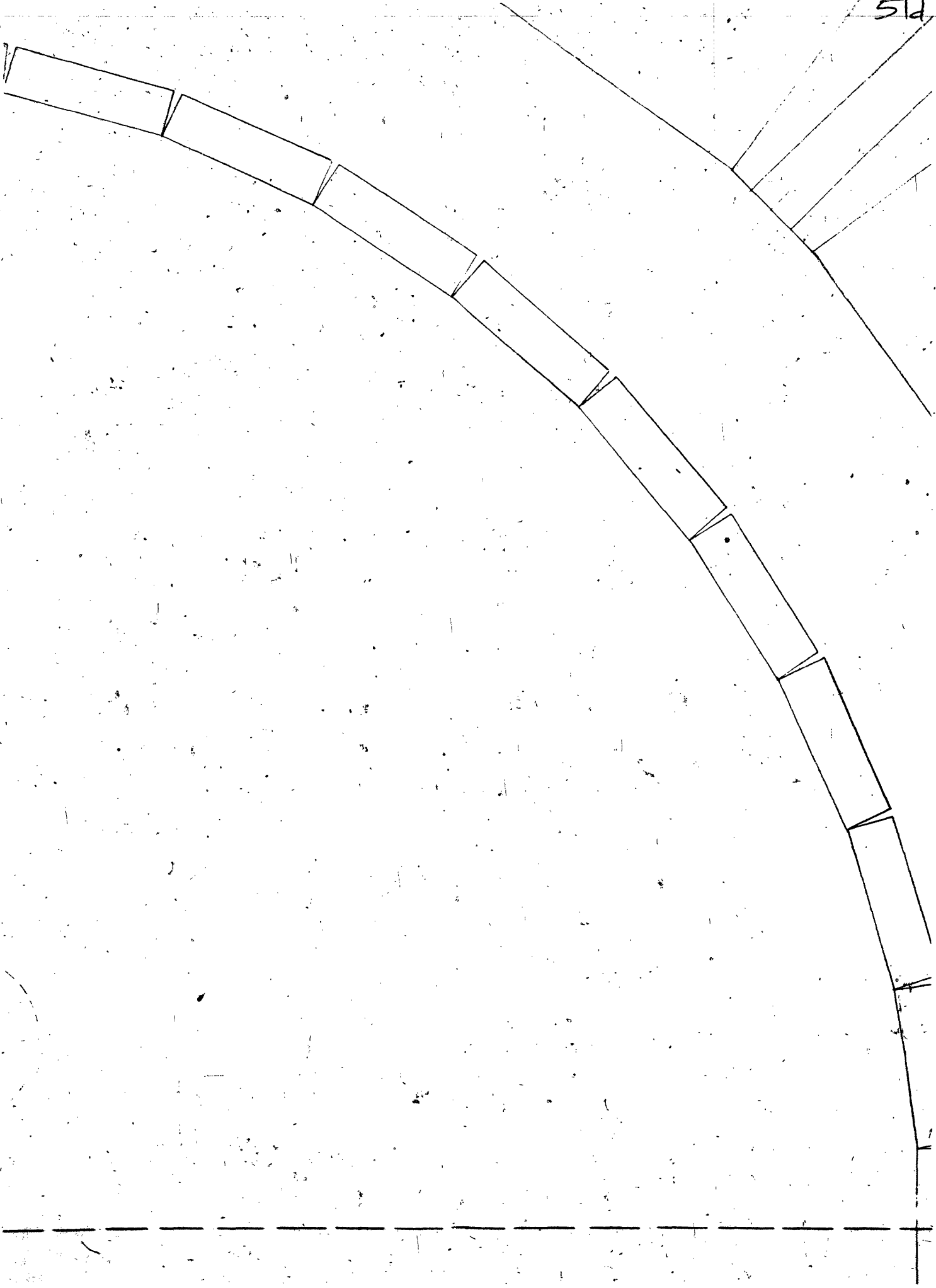
BURNER

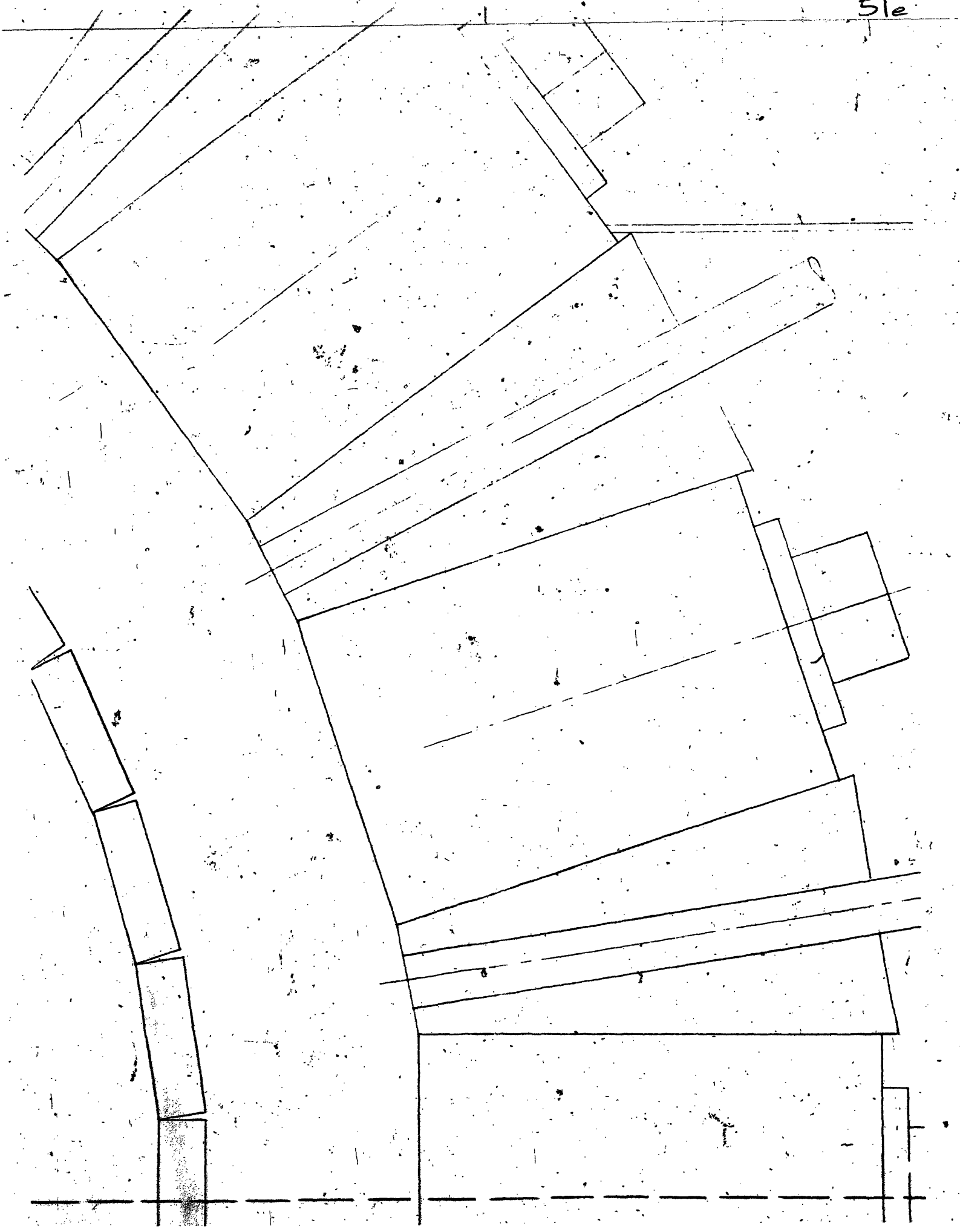
TYPICAL
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CONNECTION

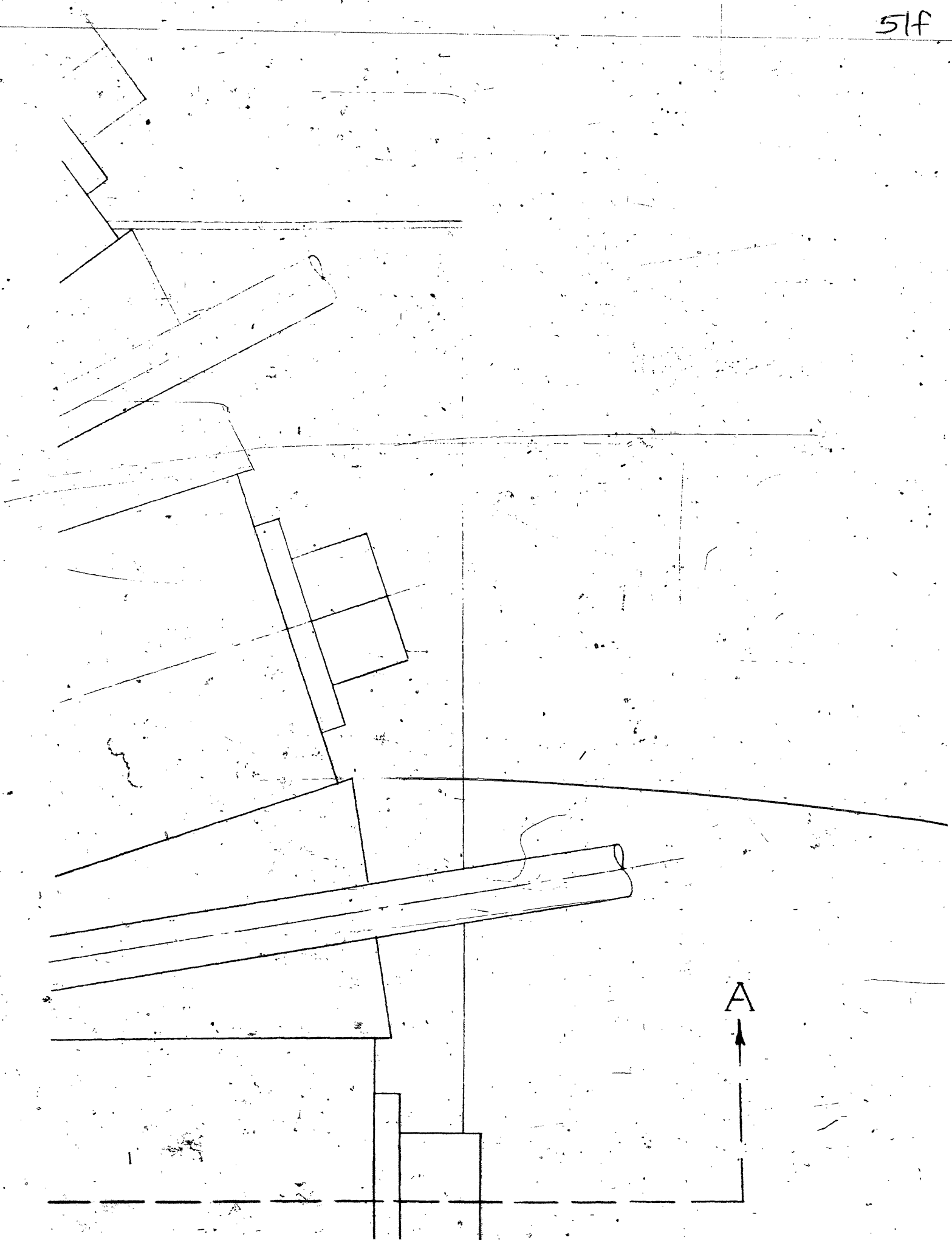


FLOW STRAIGHTENER





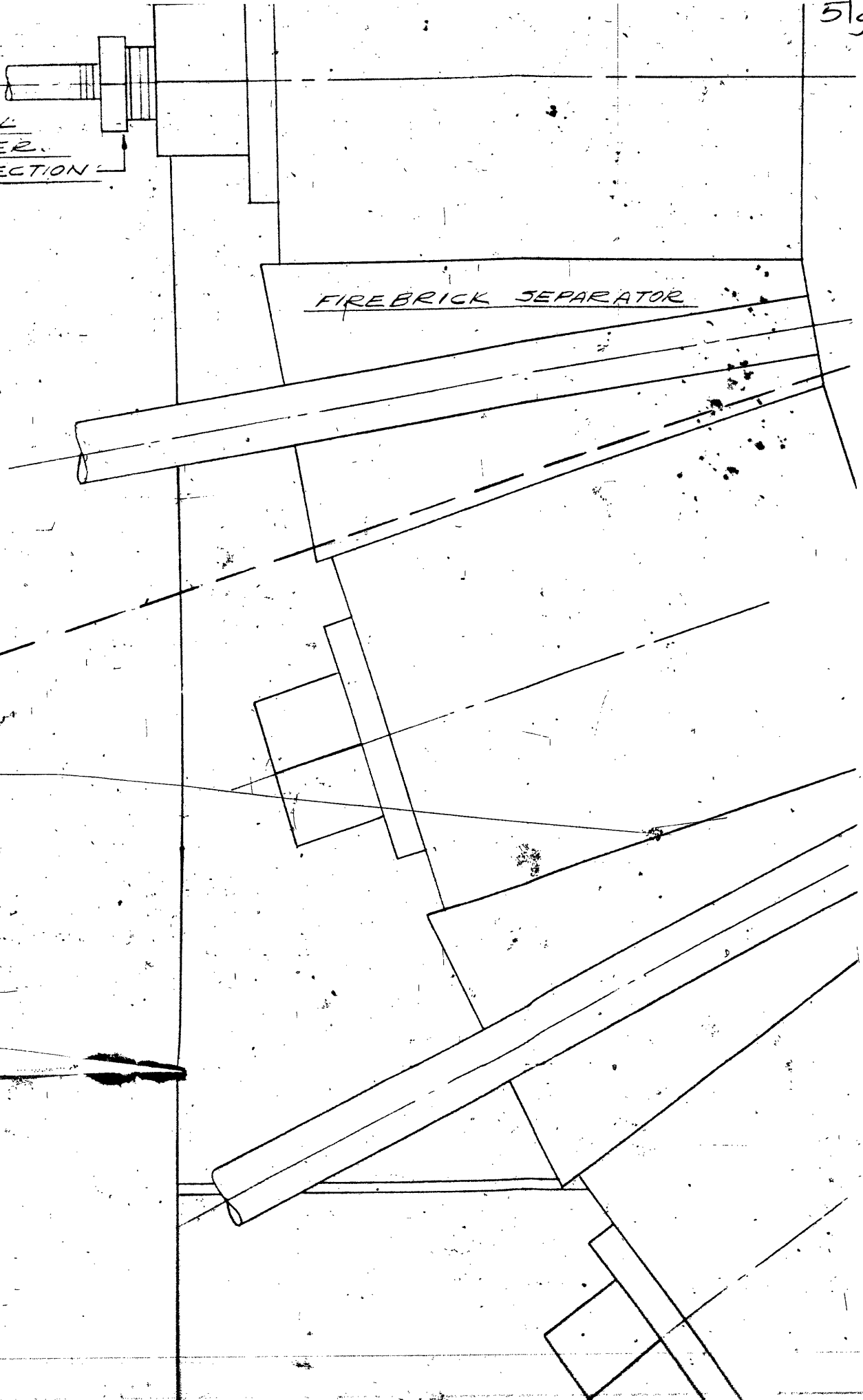




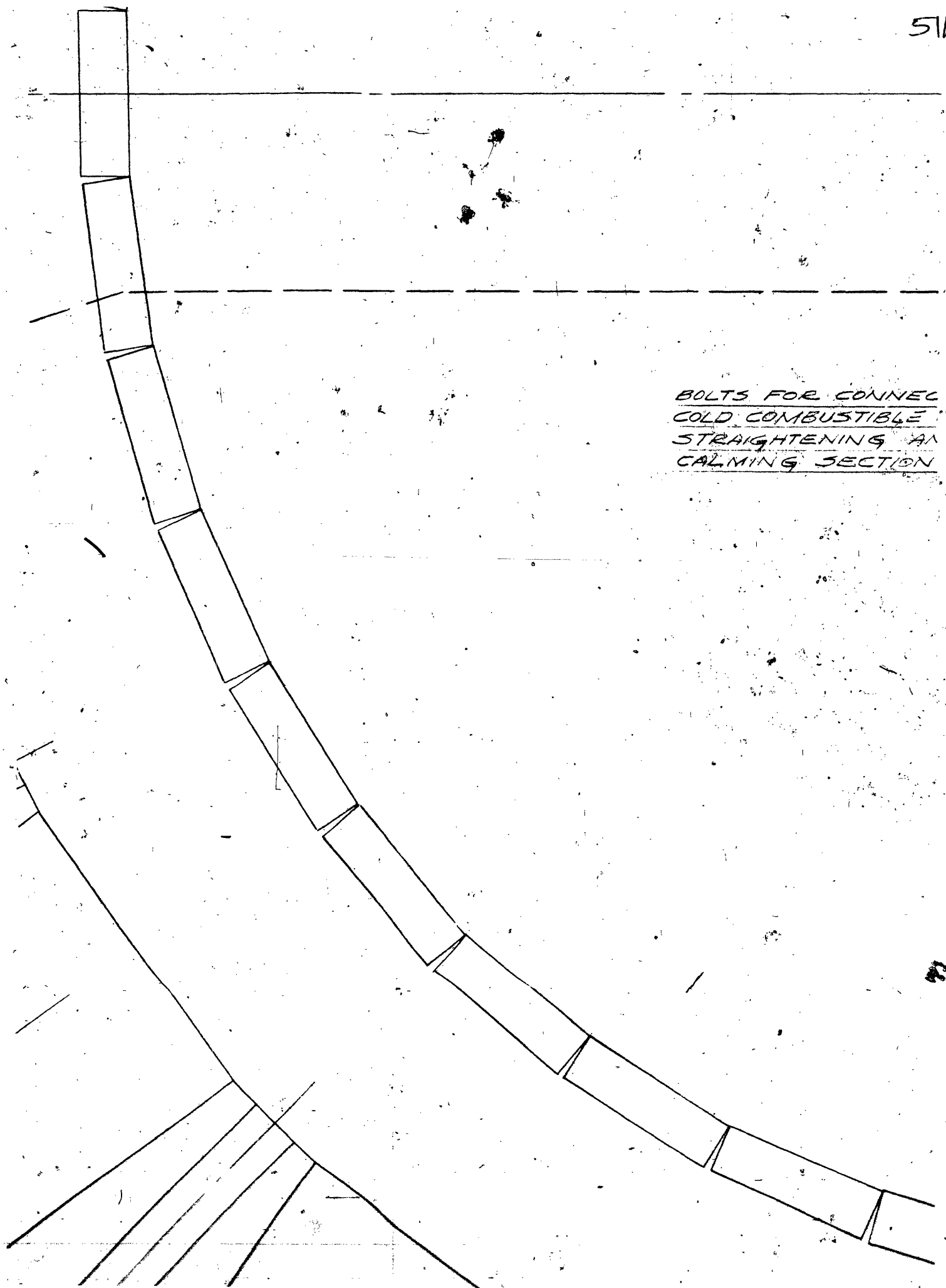
TYPICAL
BURNER
CONNECTION

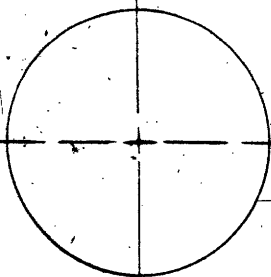
FIREBRICK SEPARATOR

A



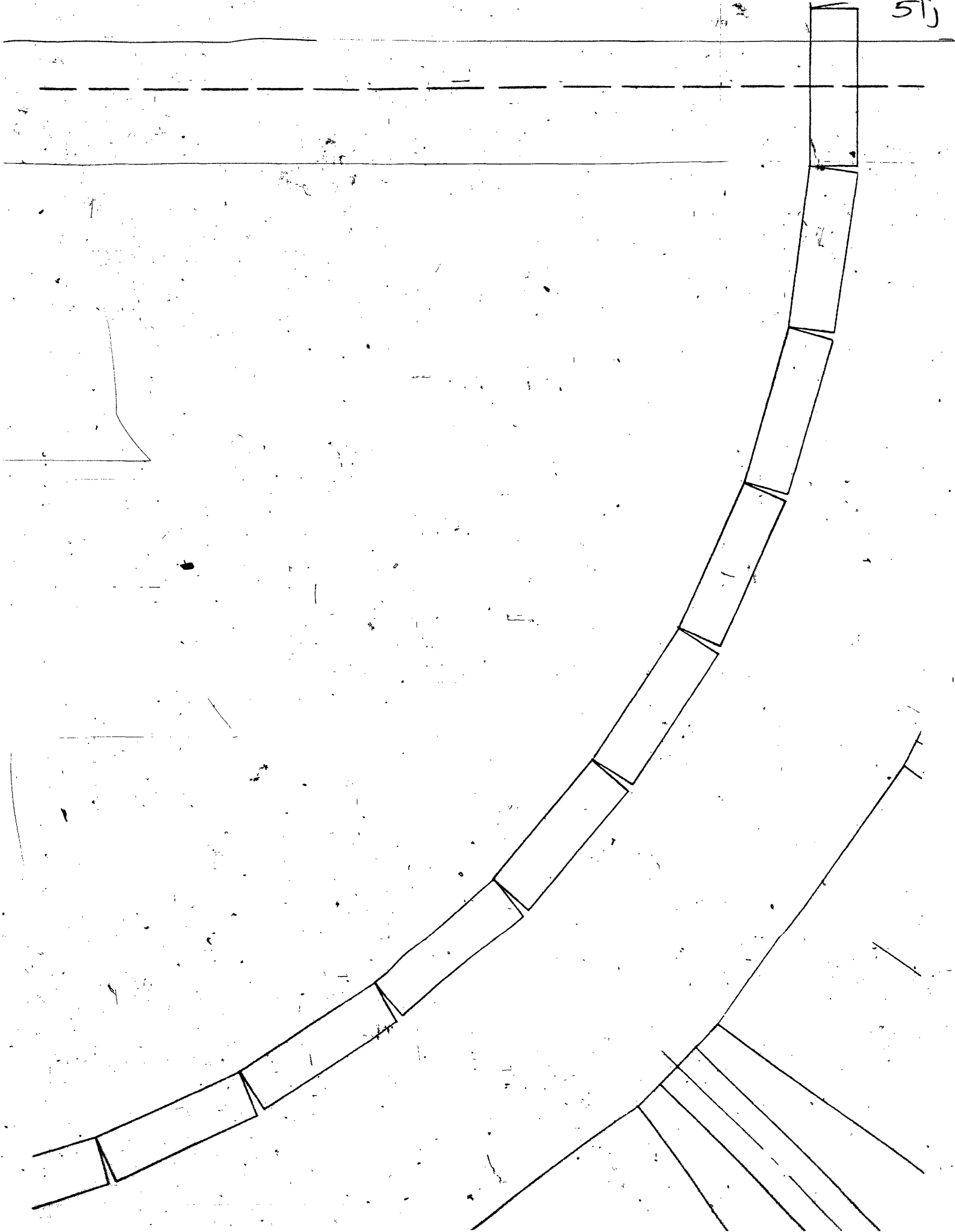
BOLTS FOR CONNEC
COLD COMBUSTIBLE
STRAIGHTENING AN
CALMING SECTION



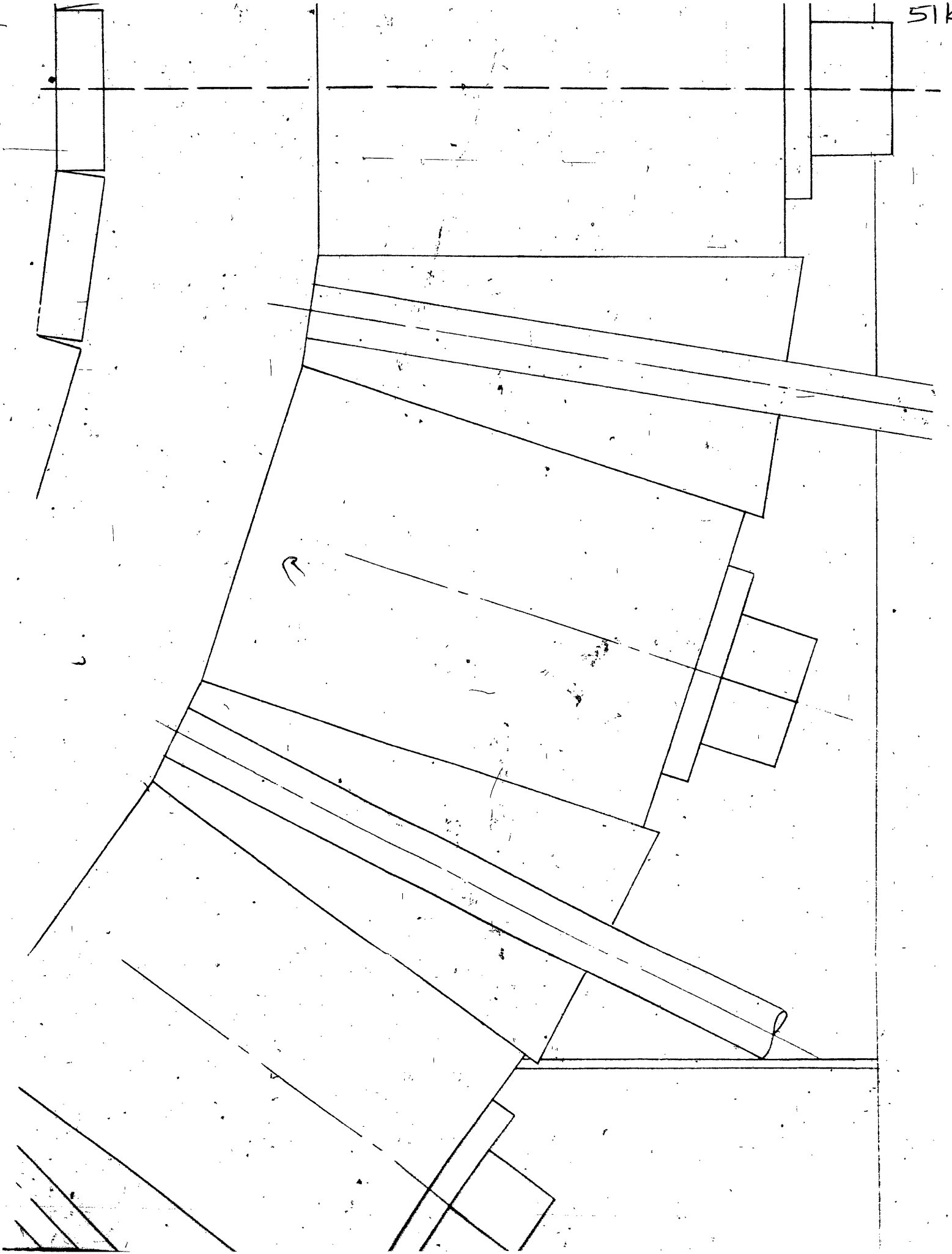


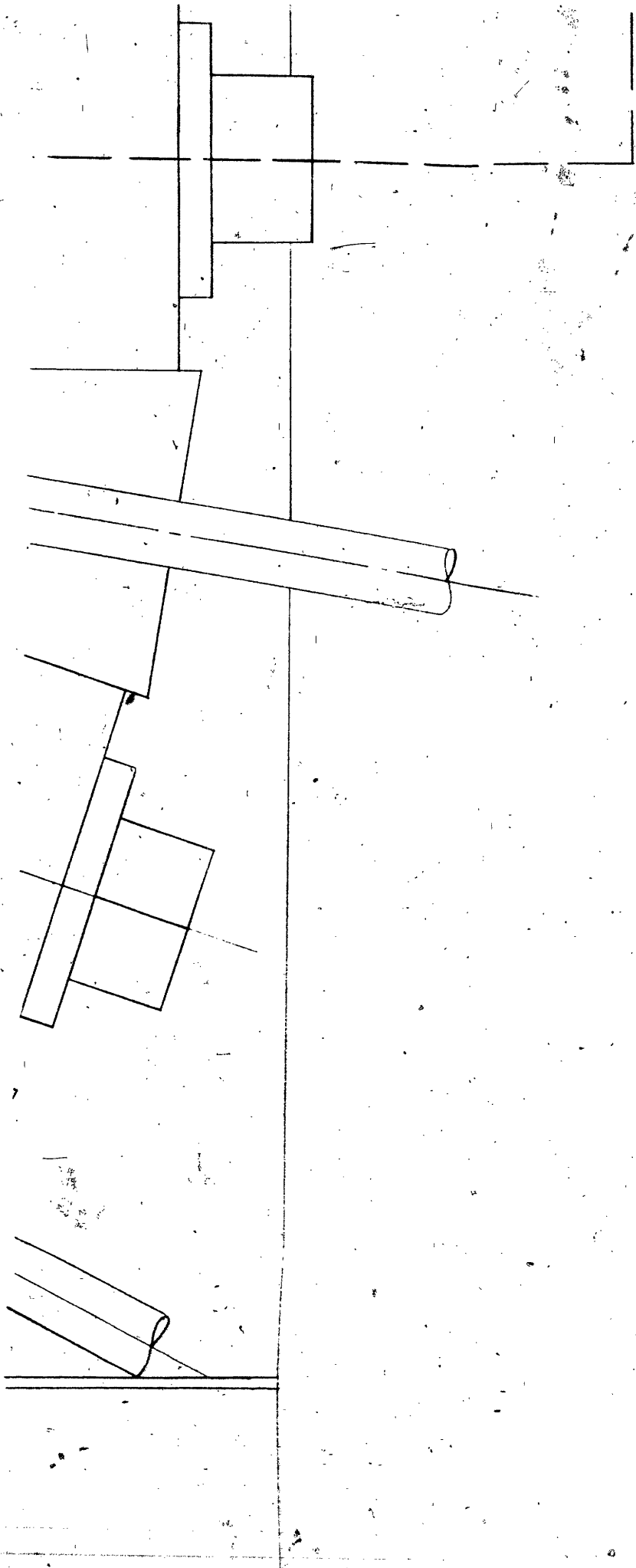
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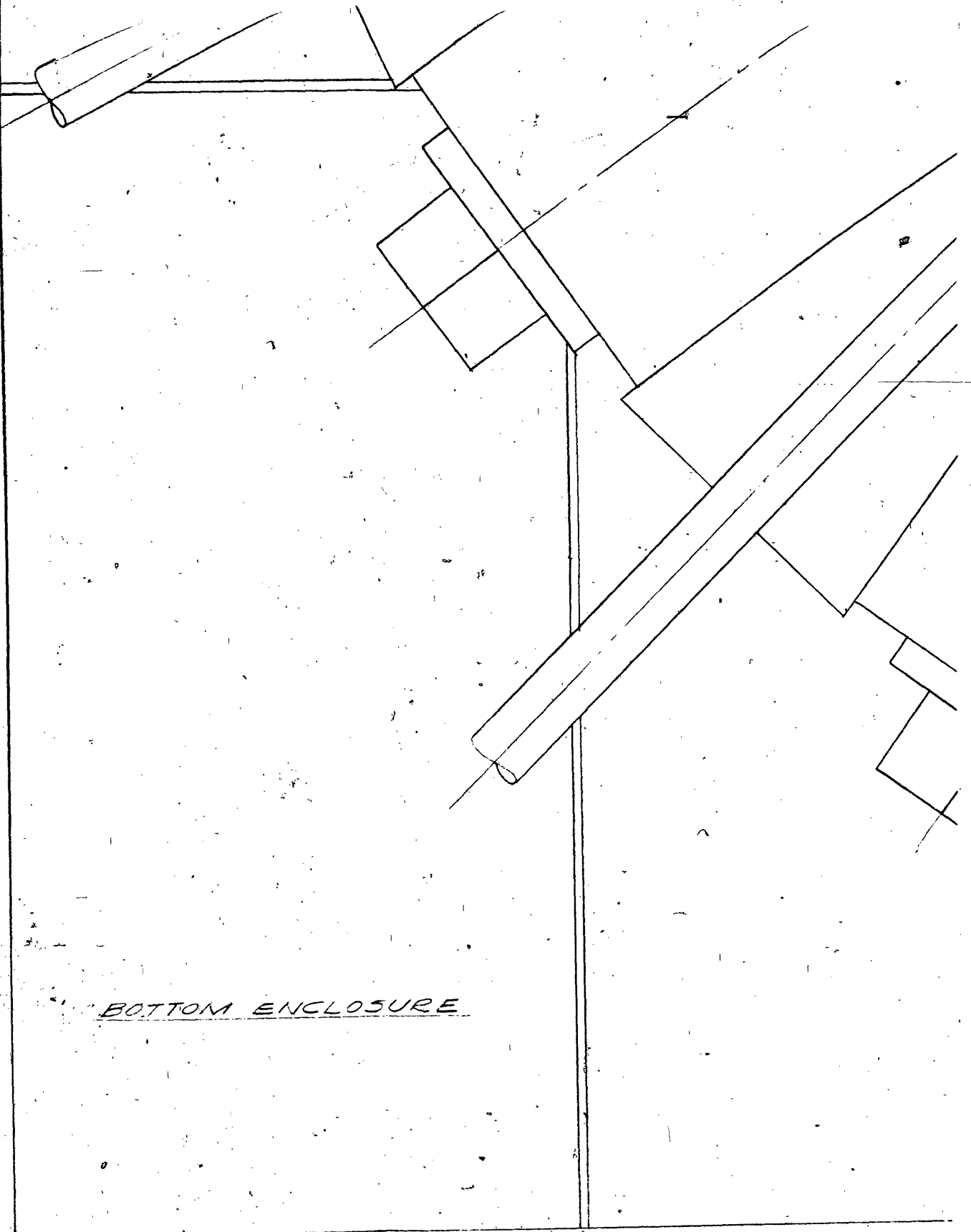


51K

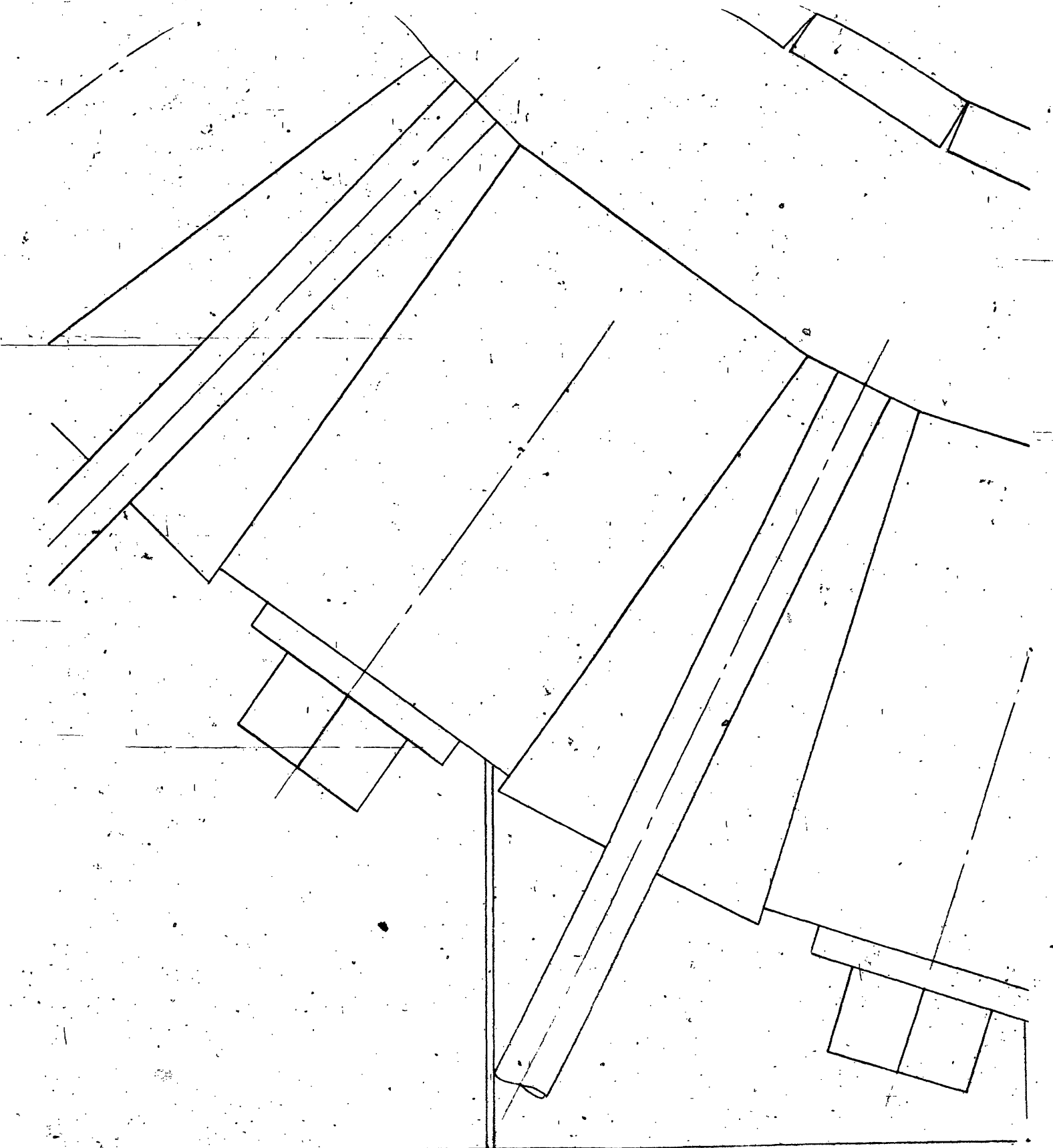


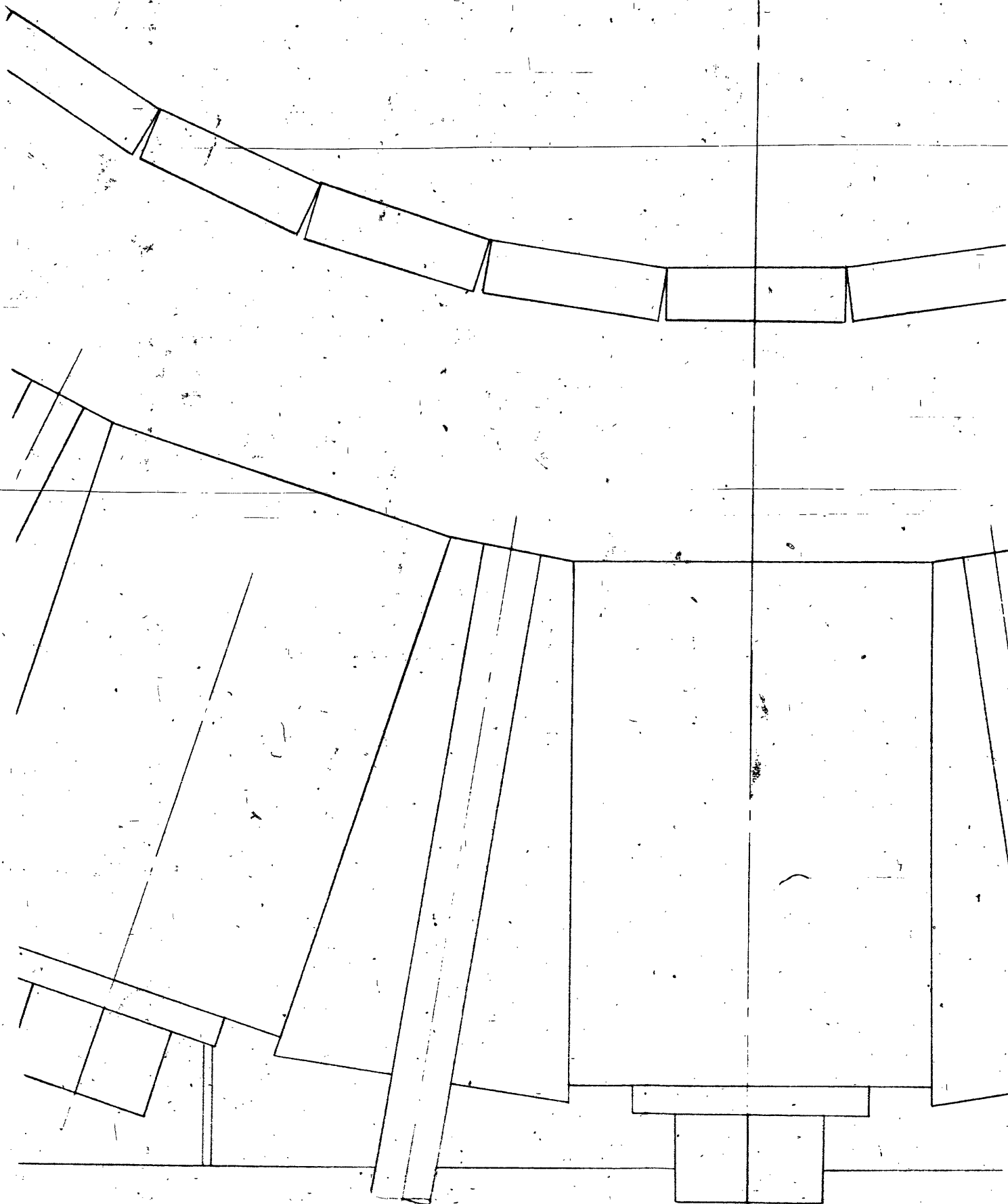


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BOTTOM ENCLOSURE





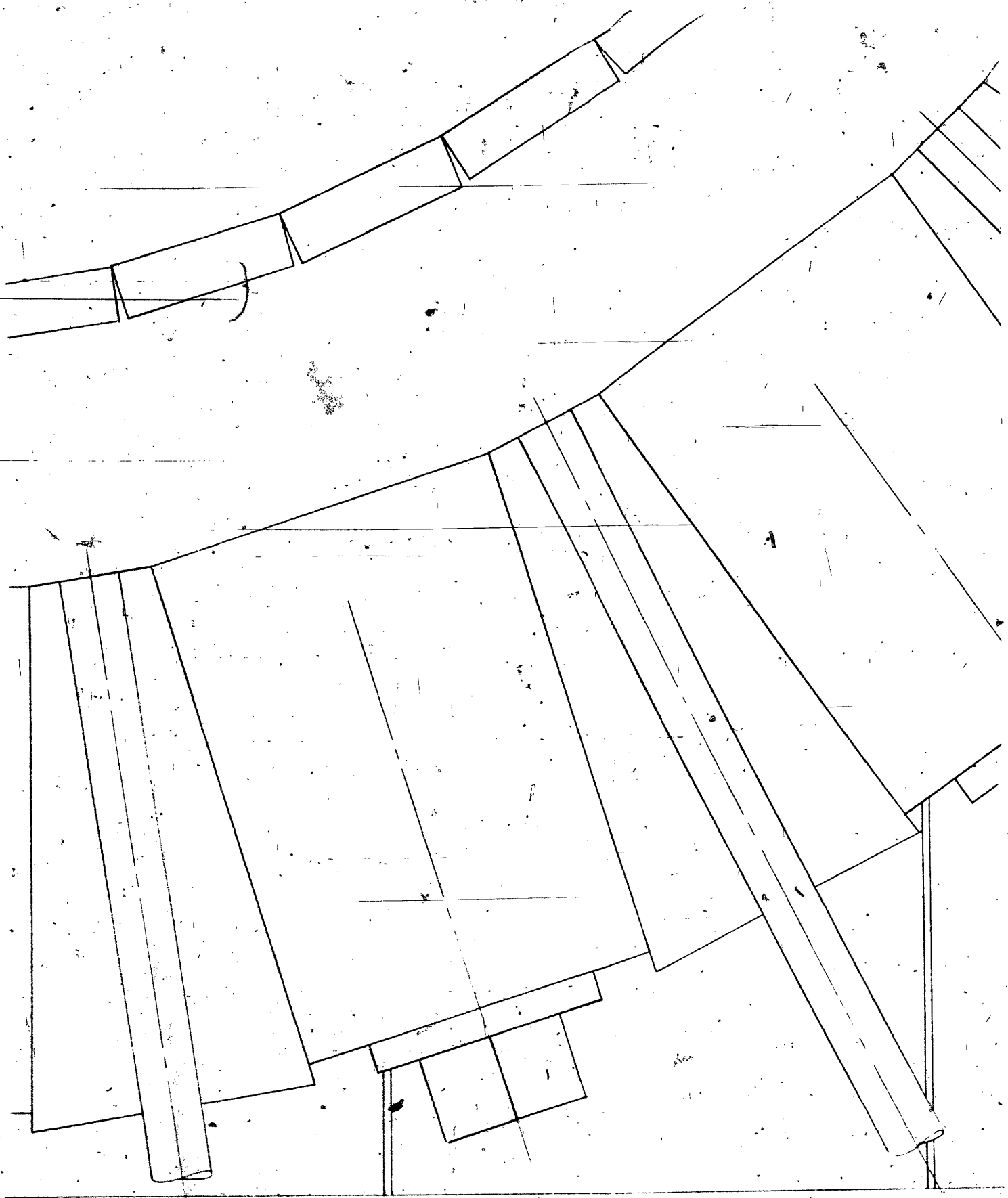
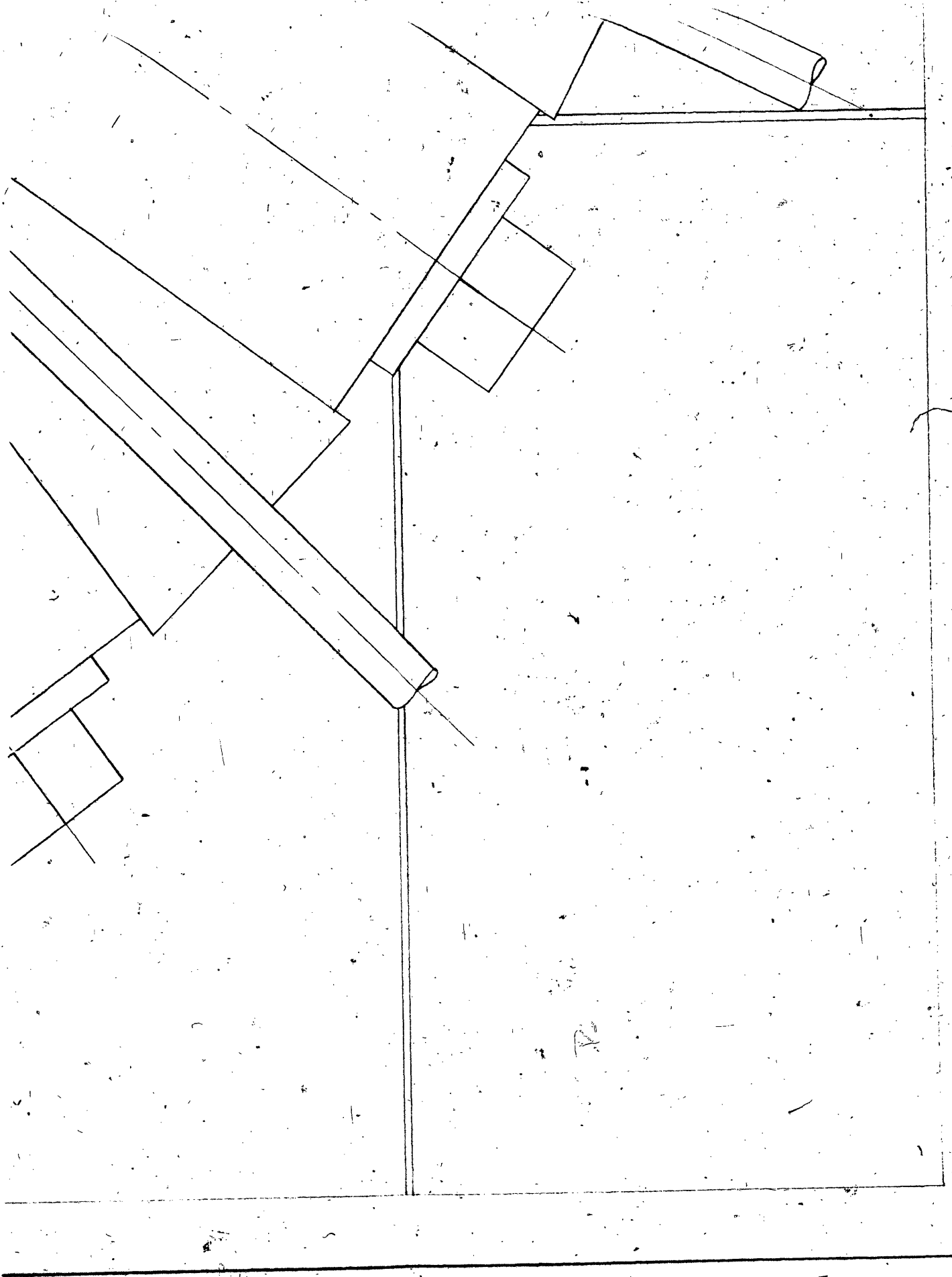


FIGURE XIV



8

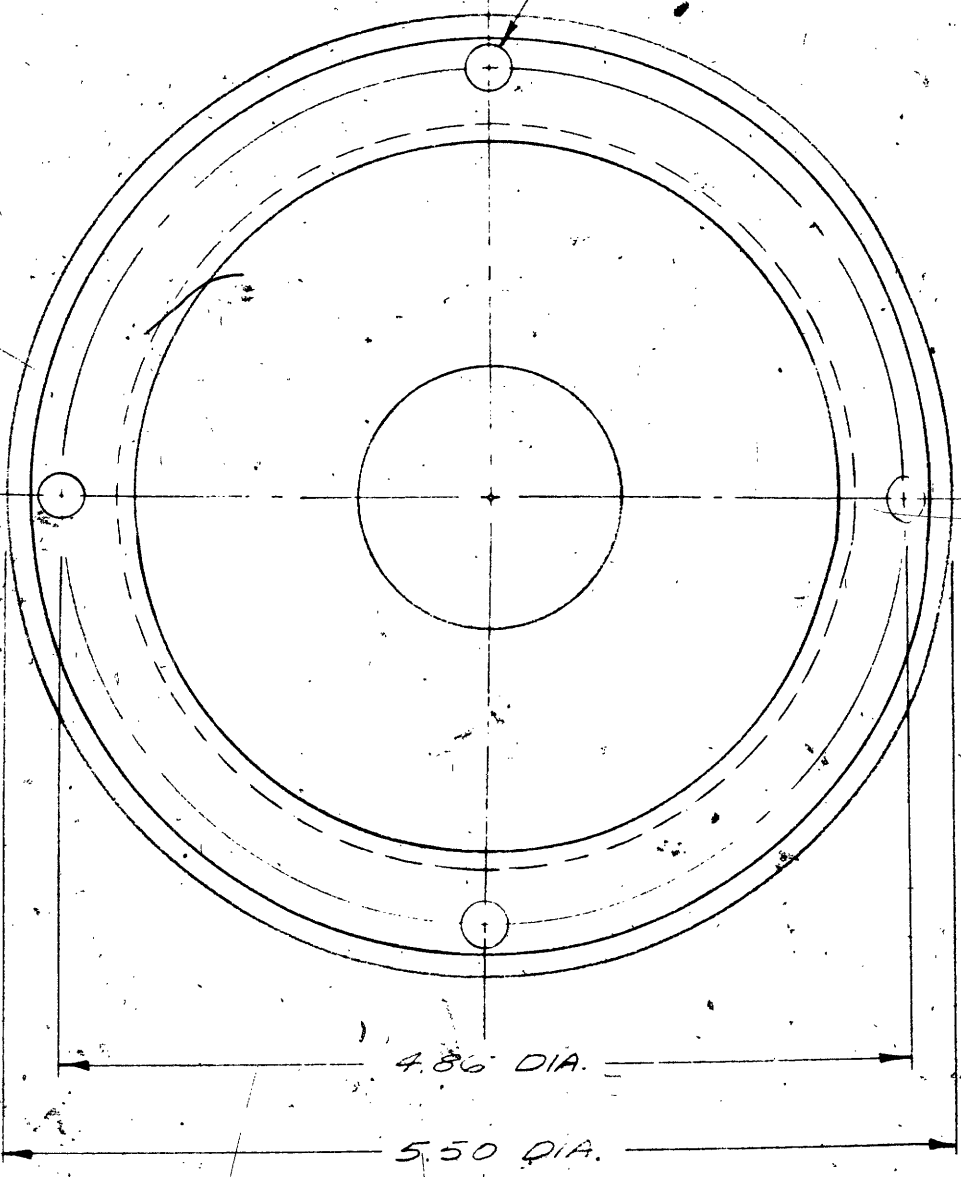
FEDERAL BUREAU OF INVESTIGATION LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

FINAL APPARATUS - OPEN POSITION

DRAWING NO.	SCALE	DATE	DRAWN BY	CHECKED BY
2	FULL	6-4-59	MERRION	

DESIGN OF FINAL APPARATUS - TOP VIEW

DRILL 4, 17/64
HOLES THROUGH,
EVENLY SPACED

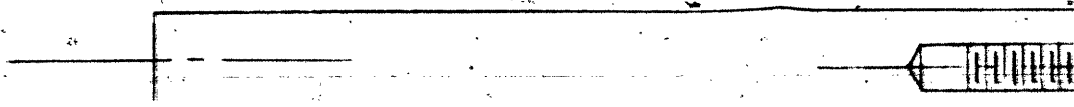
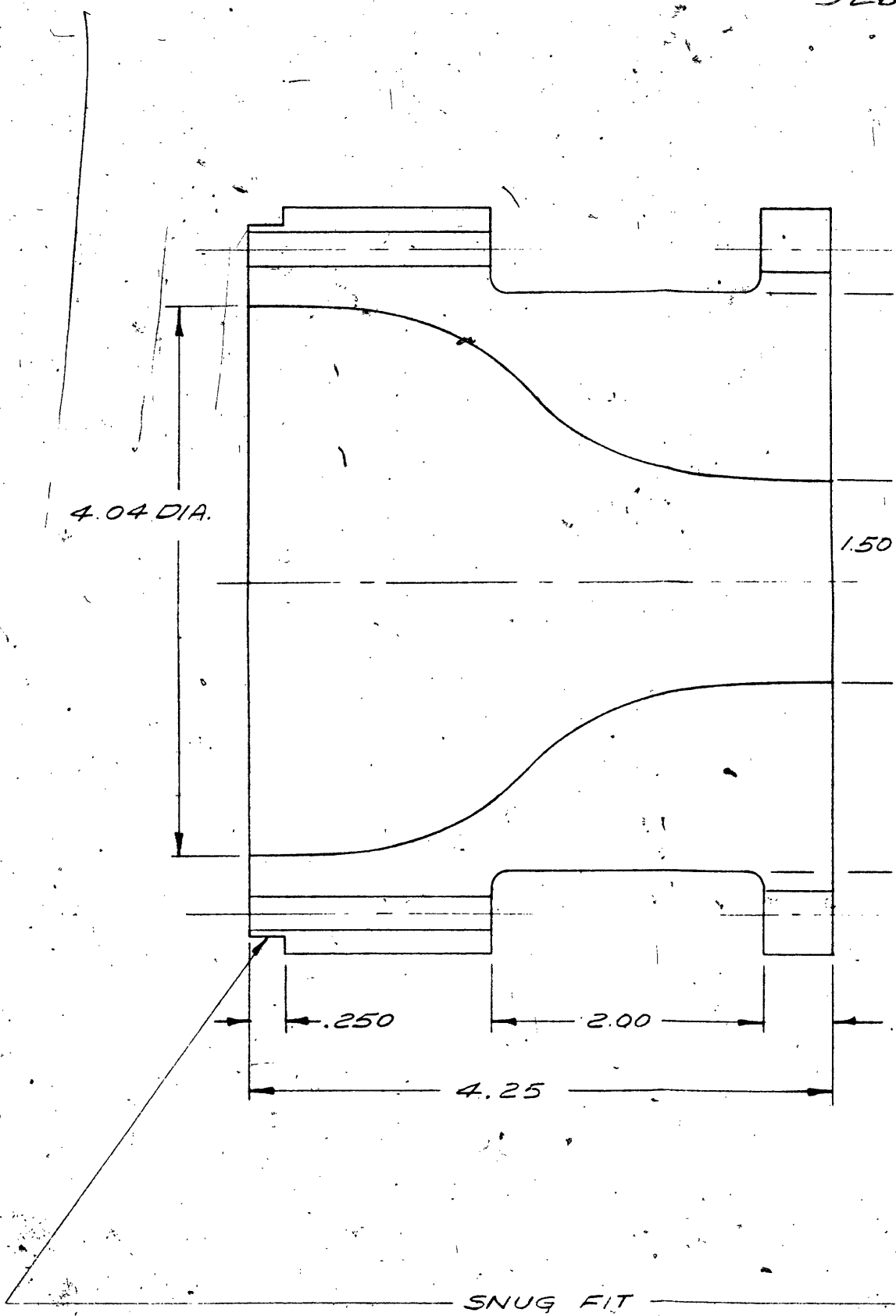


L

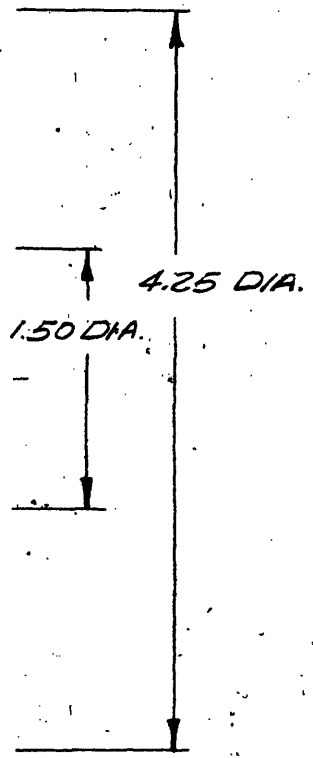
DRILL AND TAP HOLES
AFTER CONNECTING
FLANGE IS MADE



4
H,
D

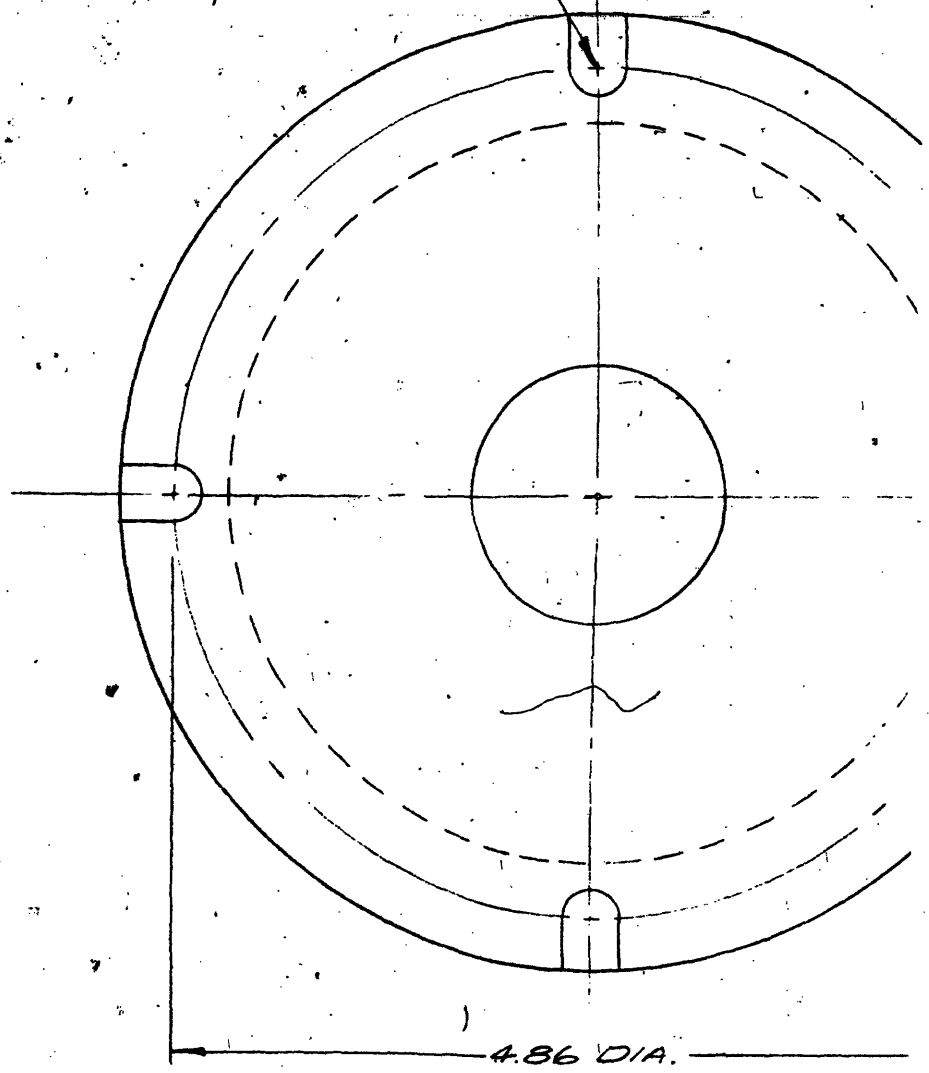


DRILL 4, 3/8 DIA.
EVENLY SPACED
MILL SLOT

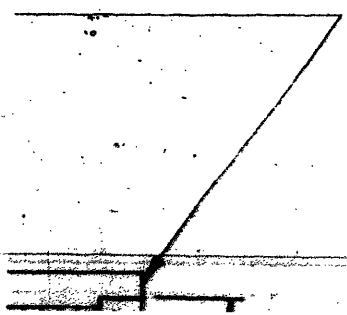


.50

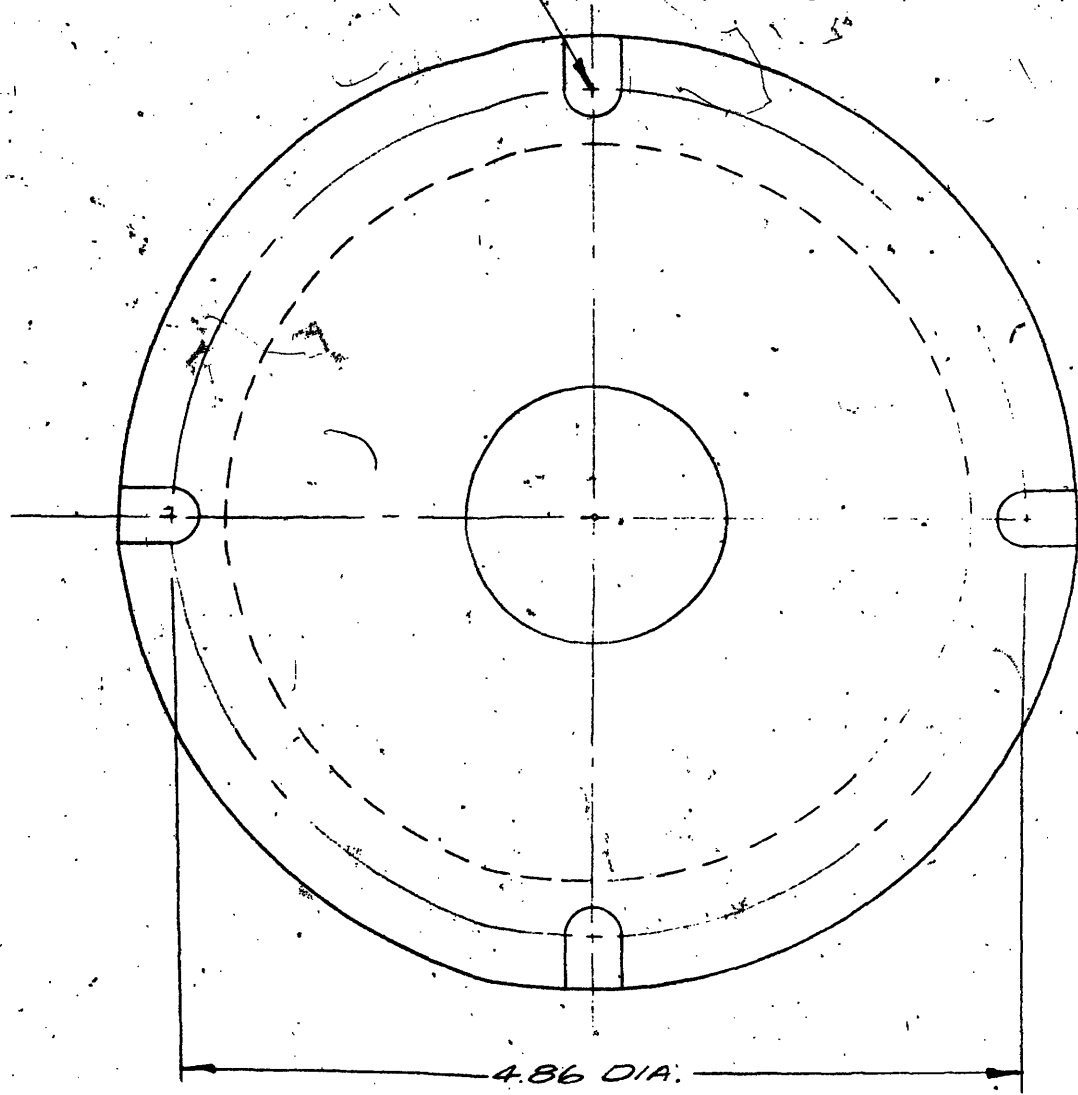
A small dimension line with the value ".50" indicating a specific width or offset.



DRILL 4 HOLES &
SPACED AND TAP
5/8 DEEP

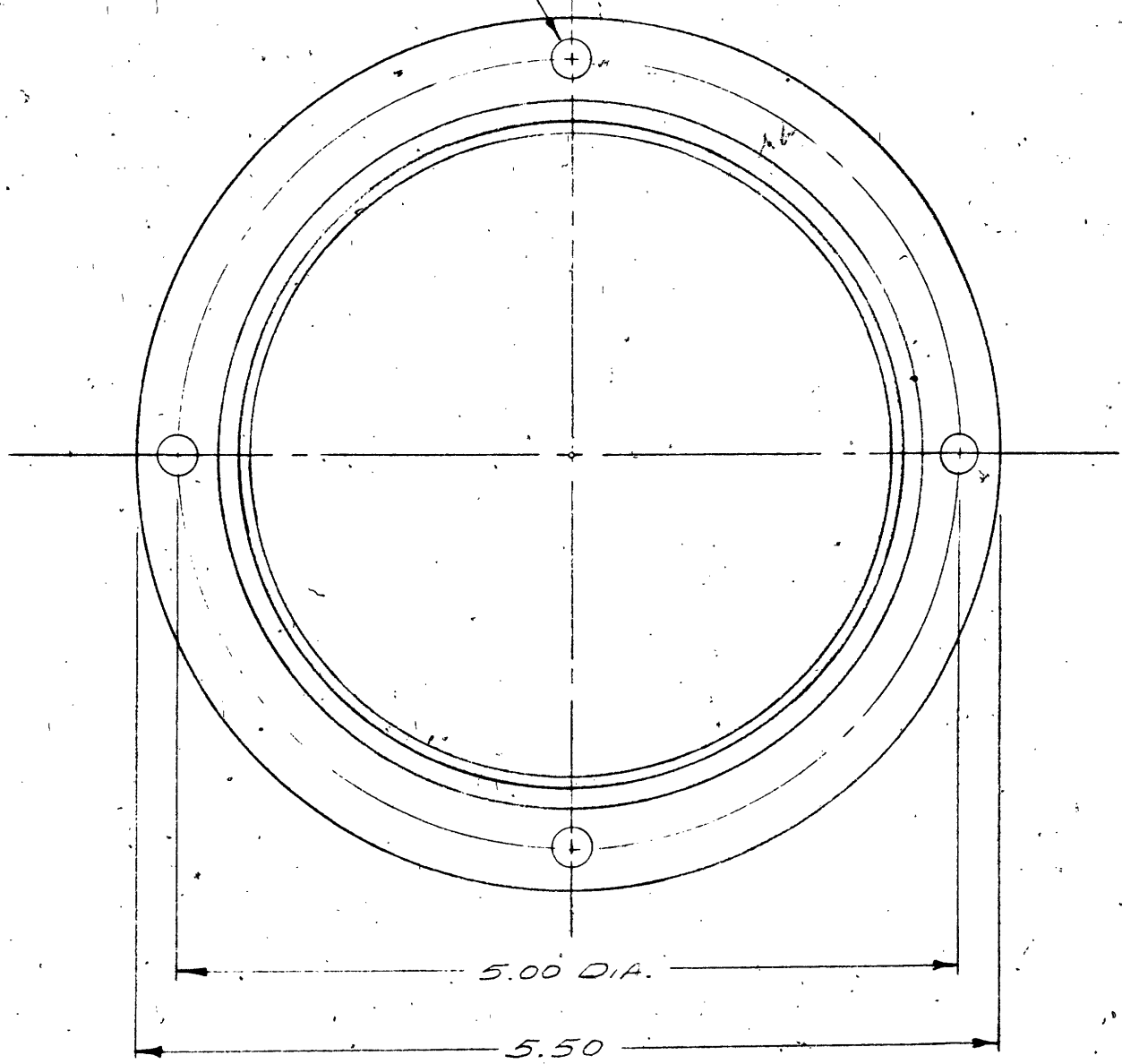


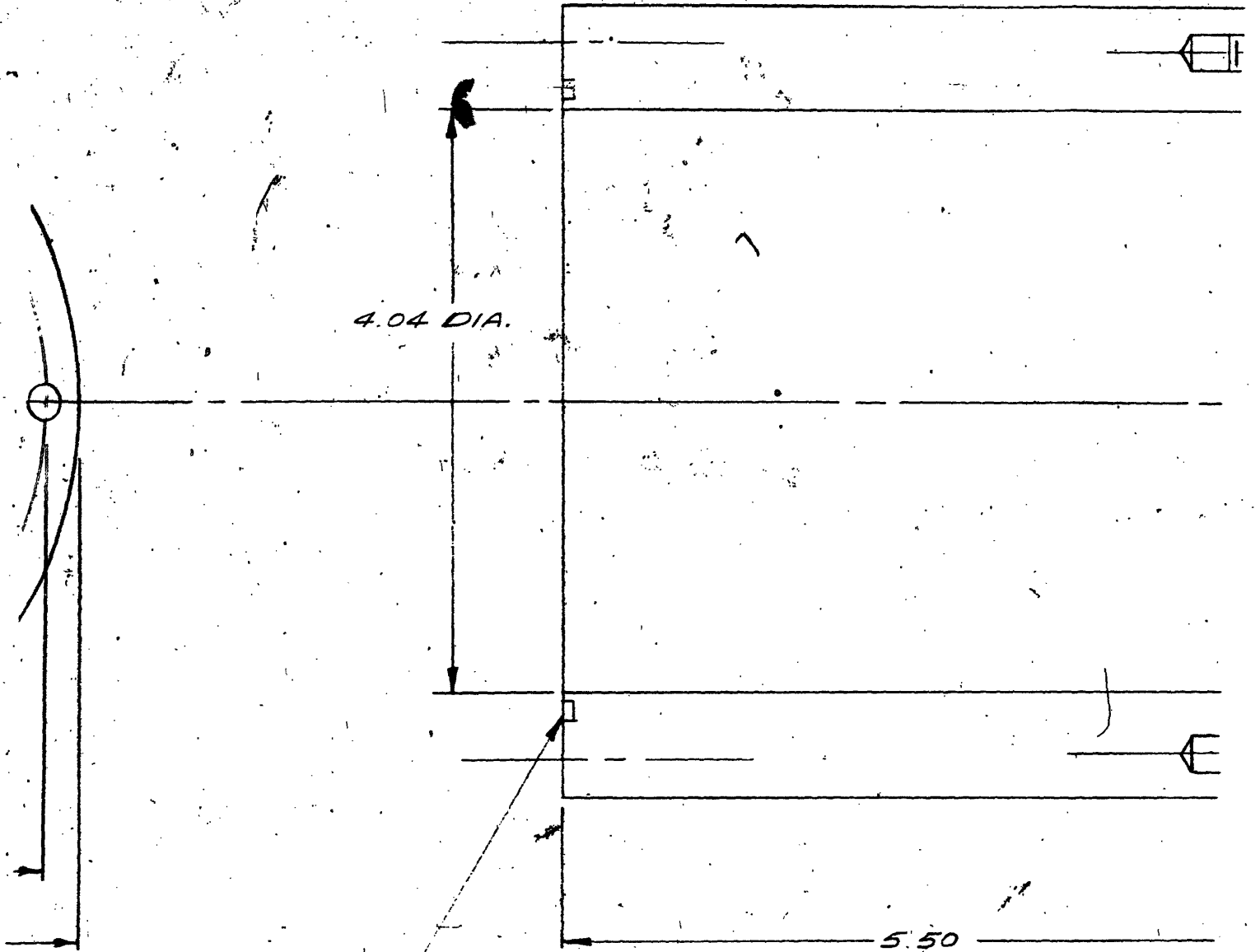
DRILL 4, 3/8 DIA. HOLES
EVENLY SPACED AND
MILL SLOT



DRILL 4 HOLES EVENLY
SPACED AND TAP 1/4 - 20
5/8 DEEP

DRILL AND TAP HOLES
AFTER CONNECTING
FLANGE IS MADE

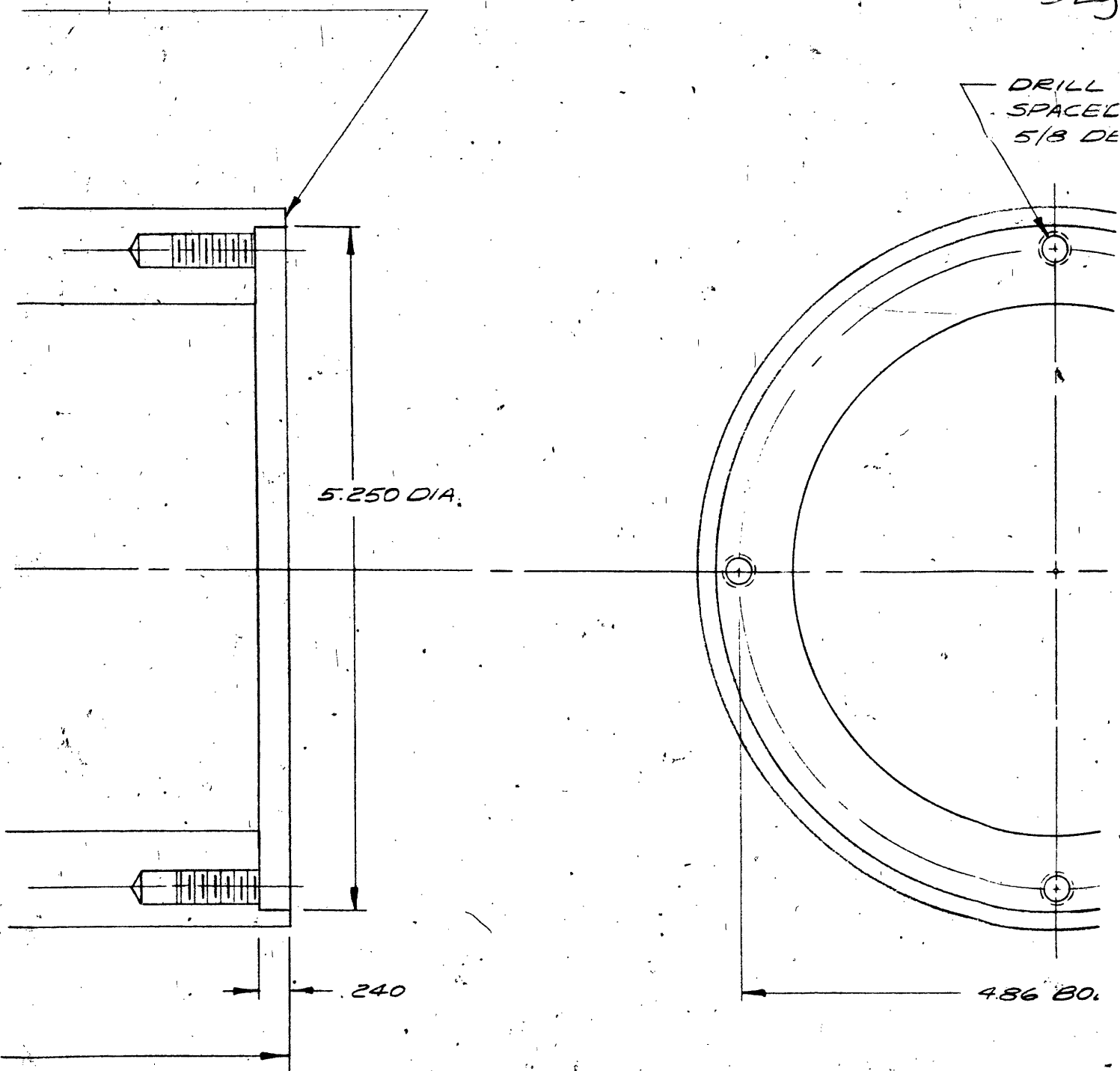




SEE CHART BELOW FOR PARKER
2-156 O-RING GROOVE DATA

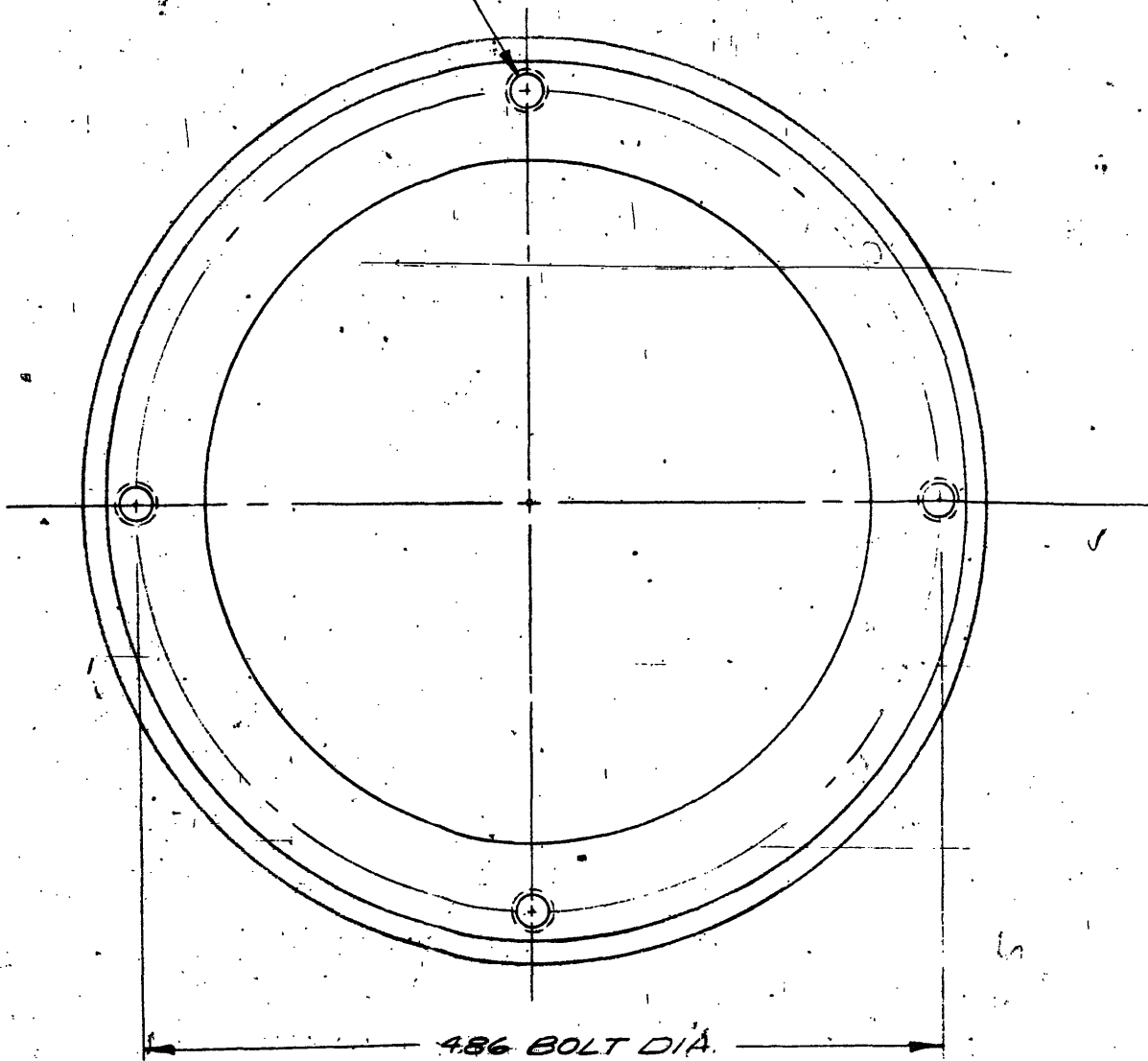
GROOVE O.D.
4.443 +.000 -.022
GROOVE WIDTH
.140 +.005 -.000
GROOVE DEPTH
.081 +.002 -.000

529



STRAIGHT

DRILL 4 HOLES EVENLY
SPACED AND TAP 1/4 -20
5/8 DEEP



INTERNAL COMBUSTION LABORATORY				
MASSACHUSETTS INSTITUTE OF TECHNOLOGY				
STRAIGHTENING AND CALMING SECTION				
DRAWING NO.	SCALE	MATERIAL	DATE	DRAWN BY
				FR MERRION

BIBLIOGRAPHY

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Merrion, David –Thesis, M.S. M.E., 1959
An Apparatus for Studying Combustion in a Laminar Zone

Pages 50-52 contain oversize map designs that were filmed in sections. They could not be scanned as single sheets due to size restrictions.